TELKOMNIKA, Vol.13, No.2, June 2015, pp. 421 ~ 431
ISSN: 1693-6930, accredited A by DIKTI, Decree No: 58/DIKTI/Kep/2013
DOI: 10.12928/TELKOMNIKA.v13i2.987

Basal Study on Power Control Strategy for Fuel Cell/Battery Hybrid Vehicle

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Abstract

In order to enhance the fuel economy of hybrid vehicle and increase the mileage of continuation of journey, the power control strategy (PCS) is as significant as component sizing in achieving optimal fuel economy of the fuel cell/battery hybrid vehicle (FCBHV). The models of FCBHV structure and optimal power control strategy are developed by electric vehicle simulation software ADVISOR which uses a hybrid backward/forward approach. The results demonstrate that the proposed control strategy can satisfy the power requirement for two standard driving cycles and achieve the power distribution among various power sources. The comprehensive comparisons with the power tracking controller (PTC) which is wide adopted in ADVISOR verify that the proposed control strategy has better rationality and validity in terms of fuel economy and dynamic property in two standard driving cycles. Therefore, the proposed strategy will provide a novel approach for the advanced power control system of FCBHV.

Keywords: *FCBHV, Power Control Strategy, ADVISOR, Driving Cycles*

1. Introduction

Hybrid vehicles are vehicles that use two or more power sources for the drive system. In contrast, ordinary internal combustion engine (ICE) vehicles use a single power source consisting of reciprocating engine, typically fueled with gasoline, to drive a complex transmission mechanism that is then coupled to the drive wheels [1],[2]. The disadvantages of ICE vehicles include low energy efficiency, excessive harmful chemical emissions, high noise level and heavy dependence on a single fuel source. Hybrid electric vehicles are one of the solutions proposed to tackle the perceived problems associated with the energy crisis and global warming [3]. Hybrid vehicles seamlessly combine two or more power sources into one drive system. The fuel cell/battery hybrid vehicle (FCBHV) merges hybrid vehicle and the hydrogen fuel cell technologies in order to replace the conventional fuel and optimize the fuel consumption.

Power control strategy (PCS) and component sizing affect vehicle performance and fuel economy considerably in FCBHV because of the multiple power sources and differences in their characteristics. Furthermore, these two important factors are coupled—different selection of component sizing should come with different design of power control strategy. Therefore, to achieve maximum fuel economy for FCBHV, optimal power control and component sizing should be determined as a combined package. Our research has formulated and solved a power control problem of a FCBHV. Development of the power control strategy is one of the important tasks in developing hybrid vehicles and relatively many literatures can be found. Y. Guezennec et al. [4] solved the supervisory control problem of a FCBHV as a quasi-static optimization problem and found that hybridization can significantly improve the fuel economy of FCBHV. Wang Y et al. [5] used the equivalent consumption minimization strategy to determine an optimal power distribution for a fuel cell/supercapacitor hybrid vehicle. The concept of equivalent factors in hybrid electric vehicles has been described by Xiaolan Wu et al. [6]. In the same research, they also compared their power control result to deterministic dynamic programming result, which can lead to a global optimality.

As a promising technology fuel cells that convert chemical energy of the fuel into electricity without combustion are studied worldwide with an aim to improve the power output, lower the cost and extend the life of operation for widespread applications. The fuel cells are generally viewed as a dependable power source for many applications, such as hybrid vehicle,

Received November 11, 2014; Revised March 16, 2015; Accepted April 4, 2015

distributed power generation, and portable power source [7]-[9]. Due to slow dynamic characteristic of fuel cell, a FCBHV has been proposed. The power control of hybrid vehicle which determines the power assignment between the fuel cell system and auxiliary energy storage devices is an important technique.

In recent years, a variety of control strategies for power control have been used to hybrid vehicle. Thounthong et al. [10] had used an innovative control law based on flatness properties for fuel cell/supercapacitor hybrid power source. Paladini et al. [11] had presented an optimal control strategy to power a vehicle with both fuel cell and battery to reduce fuel consumption. However, in these works the proposed control strategies had not adequately considered the balance between fuel economy and dynamic property of hybrid vehicle [12]. Furthermore, an appropriate intelligent control strategy had not been proposed for a hybrid vehicle. In this paper, a secondary development for electric vehicle simulation software ADVISOR is implemented based on the system architecture of FCBHV.

In order to enhance the fuel economy of hybrid vehicle and increase the mileage of continuation of journey, the PCS is as significant as component sizing in achieving optimal fuel economy of the FCBHV. Control strategies were largely based on heuristic rules, which is usually far from true-optimality. This study presents a combined power control of FCBHV, the power control algorithm was developed from stochastic dynamic programming (SDP) motivated basis functions. According to standard driving cycle conditions, the proposed control strategy is contrasted with the power tracking control strategy which is wide adopted in ADVISOR in terms of the indexes of fuel economy and dynamic property.

2. FCBHV Structure and Optimal Power Control Strategy

With the advancement in the technology of fuel cells, there is an increasing interest in using fuel cells for hybrid vehicle [13]. The FCBHV is a popular hybrid structure as Figure 1 shown. In this structure, a fuel cell system designed for vehicular propulsion application must have a power density, a startup, and a transient response similar to present-day ICE-based vehicles. A battery is generally connected across the fuel cell system to provide supplemental power for starting the system. The fuel cell system and inverter connect by a unidirectional DC/DC converter for matching voltage class. The advantages of this structure are low power and transient response demand from the fuel cell system and convenient braking energy recovery.

Figure 1 shows the FCBHV structure and key control signals for power control. FCBHV consists of several subsystems: driver, fuel cell system (FCS), battery, DC/DC converter, electric drive, and vehicle dynamics. Considering various vehicle states – such as power demand, battery state of charge (SOC), and vehicle speed – the power control system (PCS) sends the fuel cell current request to the DC/DC converter; sends the motor torque request to the electric drive; controls the regenerative braking ratio. In order to generate the motor torque requested from the PCS, the inverter draws current from the electric DC bus where the battery and the DC/DC converter are connected in parallel. The DC/DC converter can control the current flow into the DC bus, whereas the battery here is "passively" connected to the DC bus– the difference between the current draw from the inverter and the current outflow from the DC/DC converter will be compensated by the passive battery. Therefore, the power split ratio between the battery and the fuel cell system is achieved by the PCS sending the fuel cell net current request to the DC/DC converter.

The goal of power control in FBHV is to minimize fuel consumption while maintaining the battery SOC by sending adequate current request command to the DC/DC converter. To achieve this goal, optimal power control strategy needs to be designed for the PCS to balance the FCS power and the battery power. Many power control algorithms in technical literatures were designed by rule-based or heuristic methods. Those rule-based methods are simple and easy to understand because they come from engineering intuition. However, they often lack optimality or cycle-beating. Ideally, minimization of fuel consumption of hybrid vehicles can be achieved only when the driving scenario is known a priori. The deterministic dynamic programming technique can accomplish this global optimum. Then again, the result cannot be realized as a power control scheme because it is not possible to predict the future driving scenario.

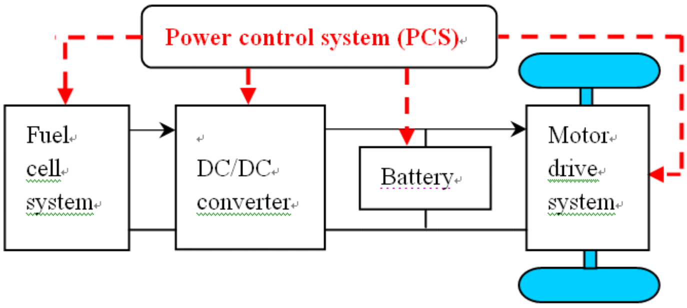


Figure 1. Drive structure of FCBHV

The power control strategy designed by the SDP approach can overcome these limitations of existing algorithms [14]. The idea of the infinite horizon SDP is that if the overall power demand is modeled as a stochastic process, an optimal controller can be designed based on the stochastic model. First, the driver power demand is modeled as a discrete-time stochastic dynamic process by using a Markov chain model, which is constructed from standard driving cycles. In other words, the power demand from the drive at the next time step depends on the current power demand and vehicle speed:

$$P_{il,j} = P_r\left\{\omega = P_{dem}^{j} \middle| P_{dem} = P_{dem}^{i}, \omega_{wh} = \omega_{wh}^{l}\right\},\ \text{for } i,j = 1,2,\cdots,N_p,\ l = 1,2,\cdots N_\omega \tag{1}$$

where the power demand P_{dem} and the wheel speed ω_{wh} are quantized into grids of N_p and N_ω, respectively. Then, for the discretized state vector, x=(SOC, ω_{wh}, P_{dem}), corresponding optimal fuel cell current request command, $u = I_{fc,net,reg}$, is determined to minimize the expected cost of hydrogen consumption and battery energy usage over infinite horizon:

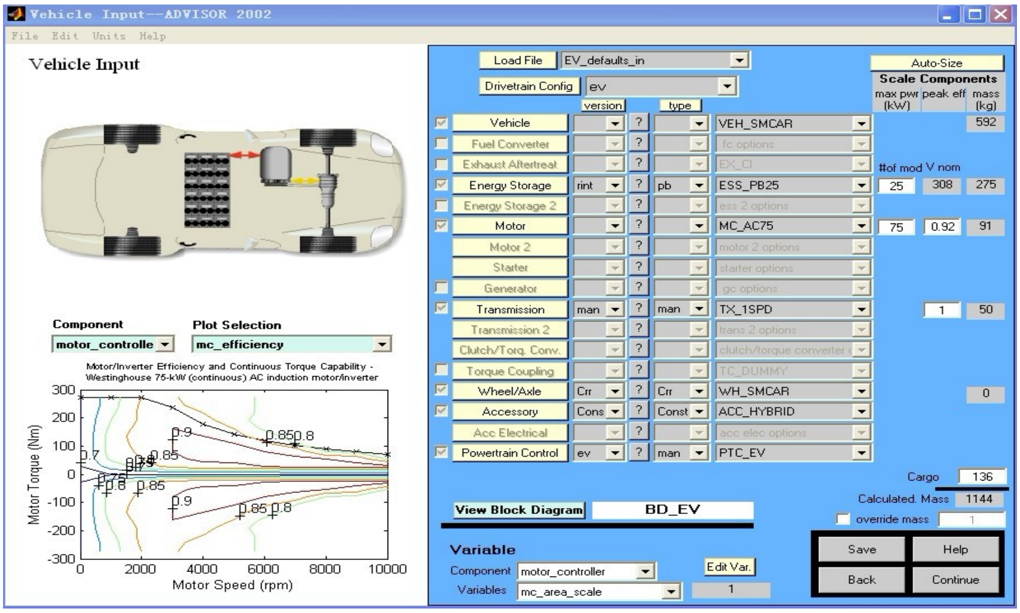
$$J = \lim_{N \to \infty} \underset{\omega k}{E}\left\{\sum_{k=0}^{N-1} \beta^k \left(W_{H_2,rct} + W_{SOC}\right)\right\} \tag{2}$$

Where $0 < \beta < 1$ the discount is factor, $W_{H_2,rct}$ the reacted hydrogen mass, and W_{SOC} penalizes the battery energy use based on the SOC value. This SDP problem can be either solved by a policy iteration or value iteration process. The resulting SDP control strategy generates optimal fuel cell current request as a function of battery SOC, wheel speed, and power demand. The control strategy achieves high fuel economy while successfully maintaining battery SOC.

3. ADVISOR MODEL OF FCBHV

ADVISOR was created in the MATLAB/Simulink environment. The program uses an iterative calculation scheme to generate outputs of a vehicle's velocity and energy use at all times during a given simulation [15]-[18]. The user manipulates a series of Graphical User Interface (GUI) screens to input various vehicle parameters and drive cycle requirements and monitor their impact on vehicle performance, fuel economy, and emissions. The three main GUI screens in ADVISOR are the vehicle input screen, the simulation parameters screen and the results screen. Examples of these screens are shown in Figure 2–4. In the vehicle input screen (Figure 2), the user builds a vehicle of interest by selecting options from a series of drop-down menus. Each list includes several preprogrammed parts for use in the vehicle. The user may also create custom components by editing the properties of each part. This feature makes ADVISOR convenient for innovative vehicle design and simulation. In the simulation parameters screen (Figure 3), the user defines the drive cycle parameters for the event over which the vehicle is to be simulated. Vehicle performance can be reviewed in the results screen (Figure

4), where fuel economy and emissions are displayed alongside detailed plots of time-dependent outputs. The user can select from awide array of output options related to speed and torque, fuel consumption, emissions, battery charge level, etc., and display up to four plots simultaneously.



Load File: EV_defaults_in
Drivetrain Config: ev

Component: motor_controlle
Plot Selection: mc_efficiency

Scale Components

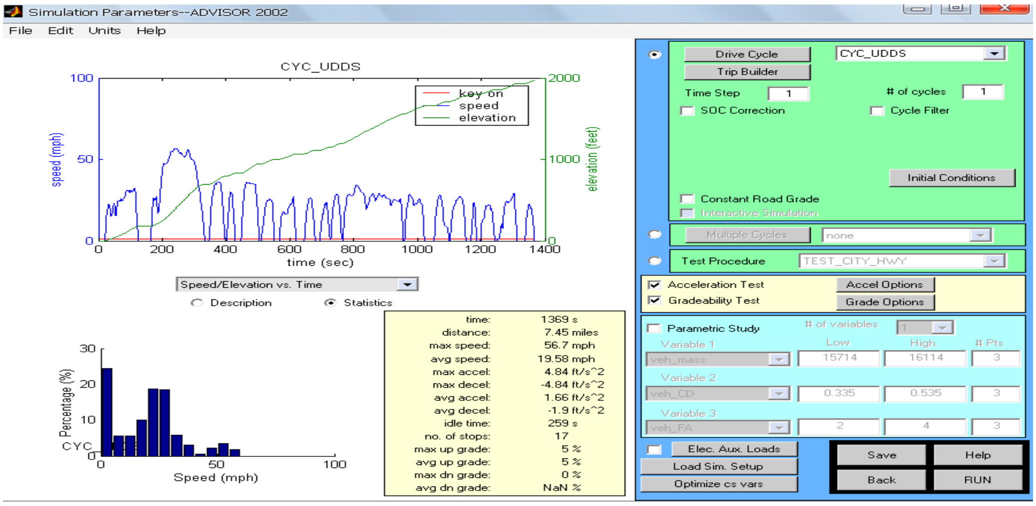
		version	type		max pwr (kW)	peak eff	mass (kg)
☑	Vehicle			VEH_SMCAR			592
☐	Fuel Converter			fc options			
☐	Exhaust Aftertreat			EX_CI			
					#of mod	V nom	
☑	Energy Storage	rint	pb	ESS_PB25	25	308	275
☐	Energy Storage 2			ess 2 options			
☑	Motor			MC_AC75	75	0.92	91
	Motor 2			motor 2 options			
	Starter			starter options			
☐	Generator			gc options			
☑	Transmission	man	man	TX_1SPD		1	50
	Transmission 2			trans 2 options			
	Clutch/Torq. Conv.			clutch/torque converter			
☐	Torque Coupling			TC_DUMMY			
☑	Wheel/Axle	Crr	Crr	WH_SMCAR			0
☑	Accessory	Cons	Const	ACC_HYBRID			
	Acc Electrical			acc elec options			
☑	Powertrain Control	ev	man	PTC_EV			

Cargo: 136
Calculated. Mass: 1144
☐ override mass: 1

View Block Diagram: BD_EV

Variable
Component: motor_controller
Variables: mc_area_scale
Edit Var.: 1

Figure 2. ADVISOR vehicle input screen



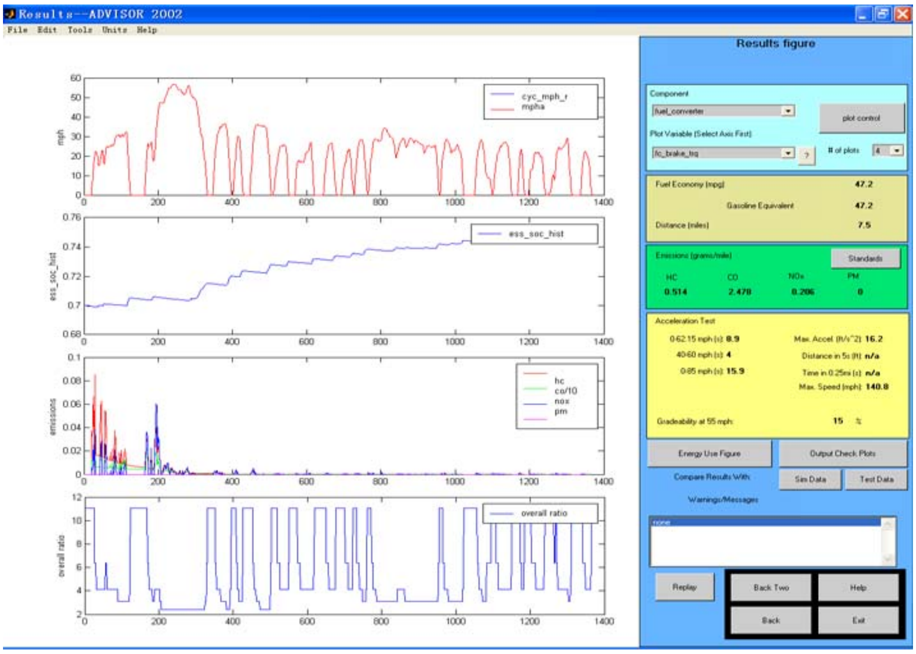
Speed/Elevation vs. Time
○ Description ● Statistics

time:	1369 s
distance:	7.45 miles
max speed:	56.7 mph
avg speed:	19.58 mph
max accel:	4.84 ft/s^2
max decel:	-4.84 ft/s^2
avg accel:	1.66 ft/s^2
avg decel:	-1.9 ft/s^2
idle time:	259 s
no. of stops:	17
max up grade:	5 %
avg up grade:	5 %
max dn grade:	0 %
avg dn grade:	NaN %

● Drive Cycle: CYC_UDDS
Time Step: 1
\# of cycles: 1
☐ SOC Correction
☐ Cycle Filter
☐ Constant Road Grade
☐ Interactive Simulation
○ Multiple Cycles: none
○ Test Procedure: TEST_CITY_HWY
☑ Acceleration Test
☑ Gradeability Test
☐ Parametric Study

	Low	High	# Pts
Variable 1: veh_mass	15714	16114	3
Variable 2: veh_CD	0.335	0.535	3
Variable 3: veh_FA	2	4	3

Figure 3. ADVISOR Simulation parameters screen



Component: fuel_converter

Plot Variable (Select Axis First): fc_brake_trq

# of plots: 4

Fuel Economy (mpg) 47.2

Gasoline Equivalent 47.2

Distance (miles) 7.5

Emissions (grams/mile)

HC	CO	NOx	PM
0.514	2.478	0.206	0

Acceleration Test

0-62.15 mph (s): 8.9

40-60 mph (s): 4

0-85 mph (s): 15.9

Max. Accel (ft/s^2): 16.2

Distance in 5s (ft): n/a

Time in 0.25mi (s): n/a

Max. Speed (mph): 140.8

Gradeability at 55 mph: 15 %

Compare Results With:

Warnings/Messages

none

Figure 4. ADVISOR Results screen

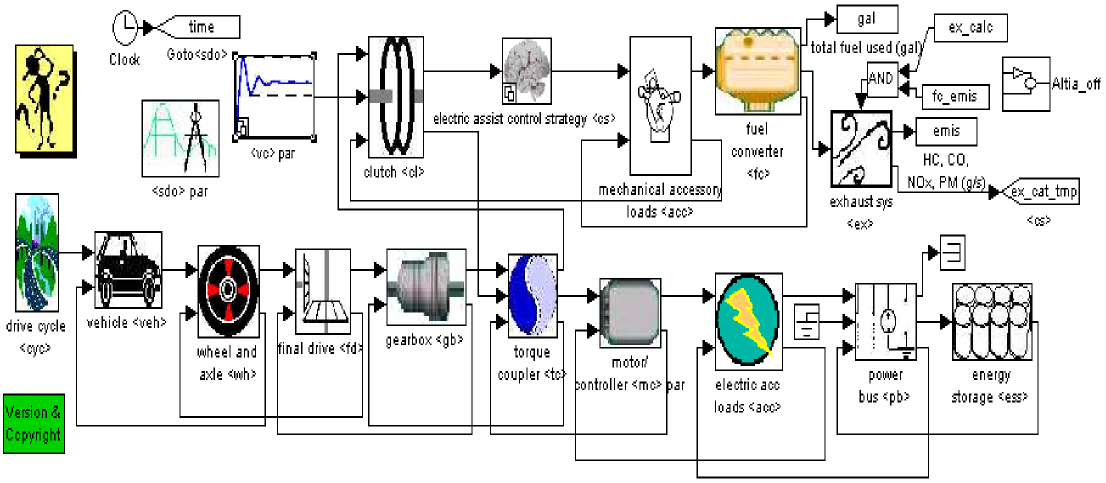


Figure 5. Block diagram of the FCBHV configuration

In this paper, a secondary development for ADVISOR is implemented based on the system architecture of FCBHV. Figure 5 show the Simulink systems for FCBHV configurations, respectively. These block diagrams represent how ADVISOR applies the drive cycle and vehicle properties to analyze the power flow. ADVISOR applies a dynamic gain to determine whether the desired power flow can be provided to each element represented in the block diagram. Through discrete time step solution methods, Simulink is able to solve the characteristic differential equations of the system. ADVISOR enables the user to modify many variables in the FCBHV. Each major component in the FCBHV can be changed independently to simulate different configurations. Our simulation was based on designs from previous City Hybrid bus. The power requirement calculations were compared to earlier drivetrains to determine the appropriate engines and motors for the simulation. Our objective was to construct a comparison in optimal fuel economy of the FCBHV, and therefore the values for some non-critical components were held constant at defaults across the PCS. A fuel cell system model based on

50 kW power-efficiency model of International Fuel Cell Company is adopted as Figure 6 shown. A resistance–capacitance (RC) equivalent circuit model is used to develop the battery model as Figure 7 shown. The validity of these models was verified by plentiful experiments [19]-[22].

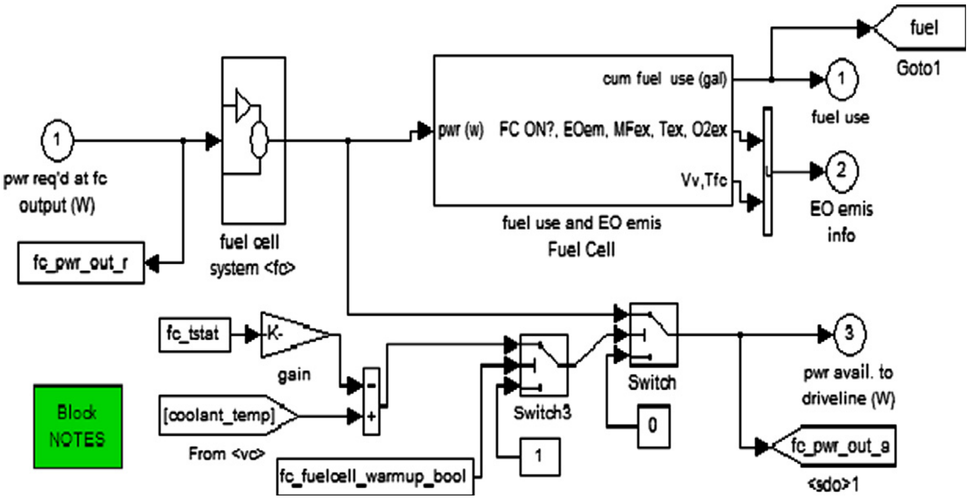


Figure 6. Simulink model of fuel cell system

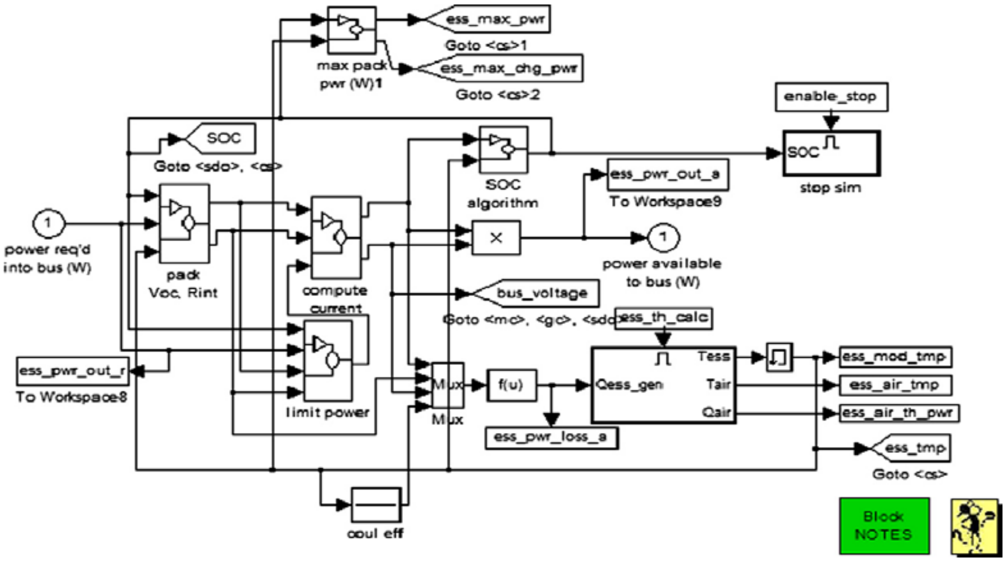


Figure 7. Simulink model of batter

4. DRIVING CYCLES AND RESULTS

The UDDS and HWFET were the standing driving cycles used throughout this study (Figure 8). The Urban Dynamometer Driving Schedule (UDDS), or “the city test”, which has a total length of 7.45 miles and an average speed of 19.59 mph, was used to represent typical drivingconditions of light duty vehicles in the city. The Highway Fuel Economy Driving Schedule (HWFET), with a higher average speed of 48.3 mph and 10.26 miles in total length, was used to represent highway driving conditions. The standard cycles were extended to 25, 50, 75, 100 and 150 miles by replication. Driving cycles from a calibrated and validated simulation network were also used in this study to verify the results achieved from standard cycles.

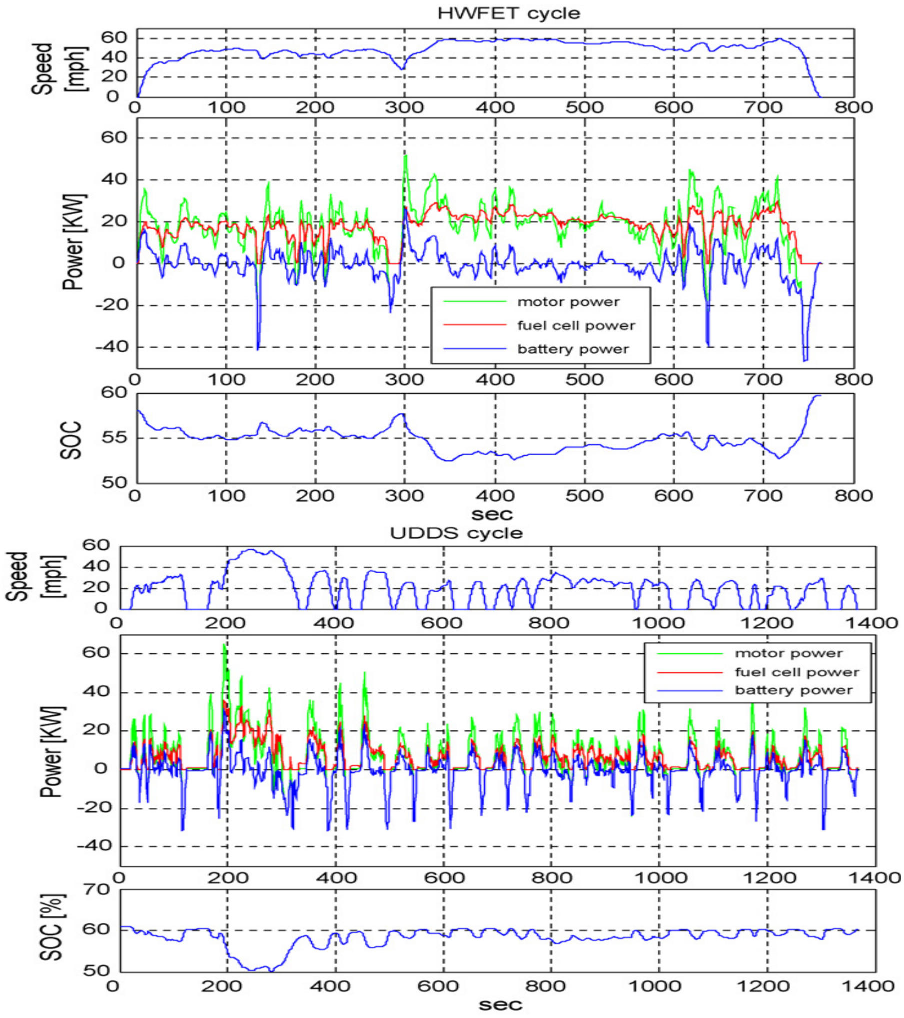


Figure 8. Comparisons between highway (above)/city (below) cycle

In order to compare the indexes of fuel economy and dynamic property of hybrid vehicle, the PCS are designed for FCBHV. In addition, according to two standard cycle conditions, the proposed control strategies are contrasted with the power following control strategy which is wide adopted in ADVISOR for FCBHV. The speed curves of PCS for FCBHV, and power tracking controller (PTC) for FCBHV can match with the required speed curves in two cycle conditions. Therefore, PCS designed can satisfy the speed requirements for two standard cycle conditions. The speed curves are shown in Figure 8. Unlike some strategies that depletes or overcharge the battery, our controller demonstrates that it can maintain the battery SOC within limited operating range. In Figure 8, the optimization result in time horizon of city and highway cycles was shown. Similar to the original SDP controller, the pseudo-SDP controller split the required motor power to the fuel cell and the battery and maintains the battery SOC.

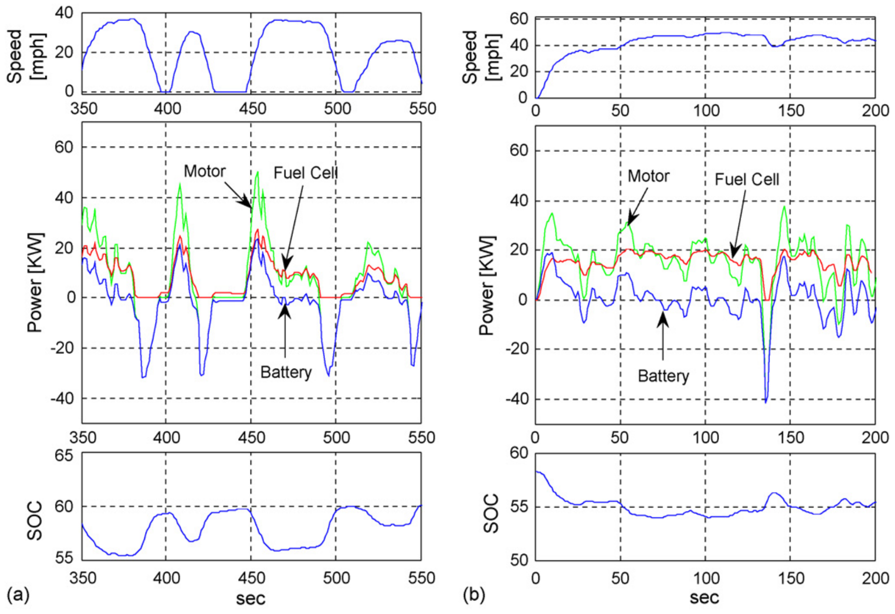


Figure 9. Comparison of optimal results for 200 s of (a) city cycle (b) highway cycle

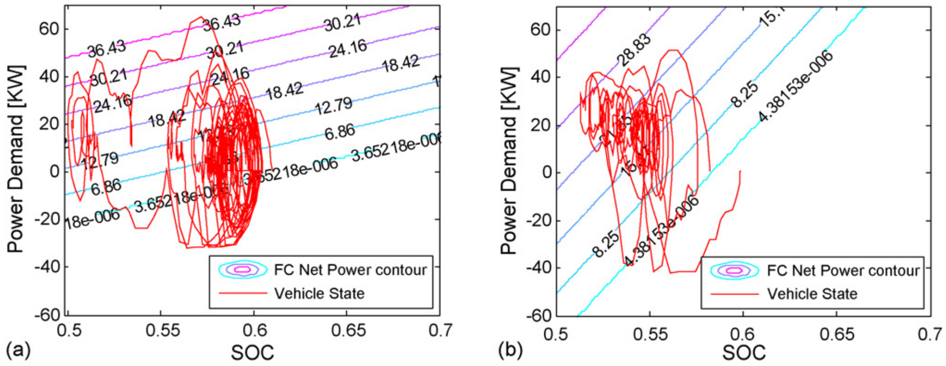


Figure 10. Optimized PCS and vehicle state trajectories (a) city cycle (b) highway cycle

In Figure 9, results for city and highway cycles are compared. The city cycle of Figure 9(a) has more accelerations/decelerations so the vehicle can capture more regenerative braking energy. Therefore, the optimized sensitivity slope of the city cycle is relatively flat compared to that of the highway cycle, i.e., $x^*_{\alpha,city} < x^*_{\alpha,highway}$ (Figure 10). Figure 9(b) shows the results for the first 200 s of highway cycle, in which the vehicle is launching and then cruising at 50 mph. When the vehicle first launched, the power demand suddenly increases and the battery helps to assist power for the FCS, of which the net power rate is limited. When the vehicle cruises, the pseudo-SDP controller runs the FCS “slow and steady” while the battery operates as an energy buffer to cover the fast dynamics of power demand [23]-[25].

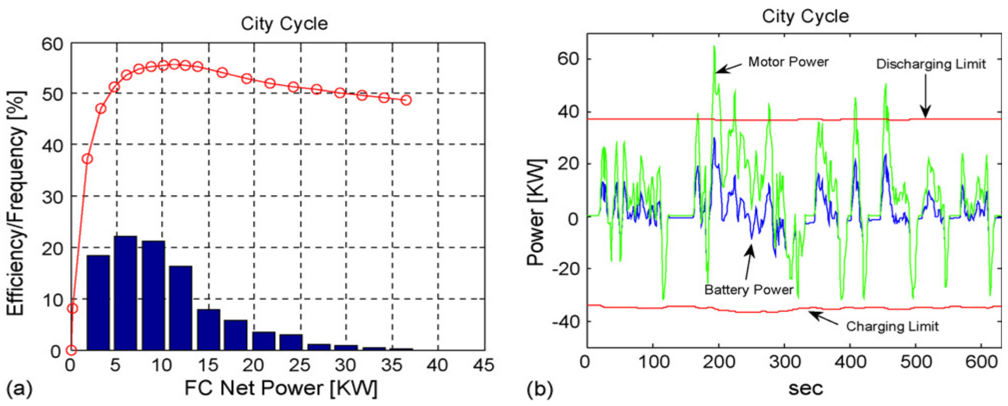


Figure 11. Optimized (a) fuel cell and (b) battery characteristics for city cycle

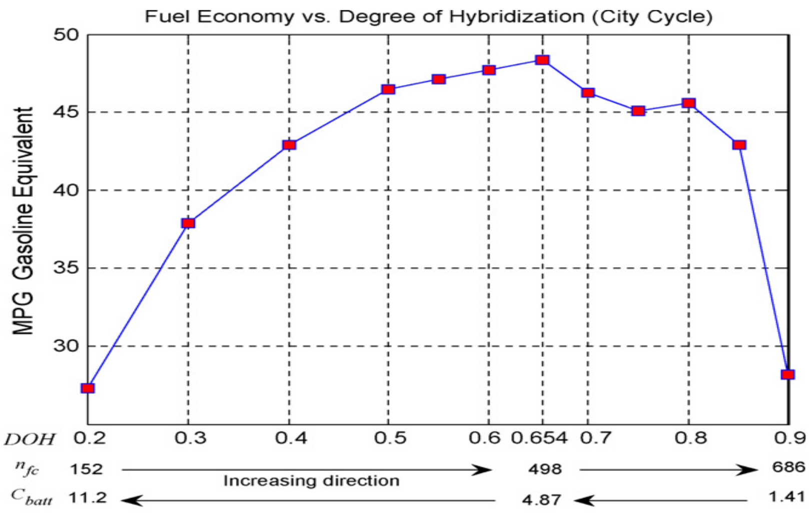


Figure 12. Effect of DOH on fuel economy for city cycle

The optimization process downsizes the compressor and increases the degree of hybridization (DOH), the DOH is the ratio of the combustion engine power to the total powertrain power. Thus, the FCS efficiency increases in the lower net power range from 0 to 26 kW, where the optimized fuel cell (FC) engine primarily operates (Figure 11). The maximum efficiency of the optimized FC engine is around 56%. Although the downsized compressor here reduces the maximum net power of the FCS, the optimized pseudo-SDP controller successfully runs the FCS within the reduced maximum net power limit. Figure 11(b) shows that even though the increased DOH reduces the battery size, the optimized battery design can still capture the majority of regenerative braking energy within its reduced power limit. If fuel cell vehicles go into production in the near future, their degree of hybridization will significantly impact the vehicle price due to high manufacturing and material costs of fuel cells and batteries [26]-[29]. Therefore, by examining the effect of DOH on fuel economy, car manufacturers can determine the trade-off between fuel savings and manufacturing costs.

Figure 12 illustrates the effect of the DOH on fuel economy for the city cycle. To obtain each point of the graph, the DOH value is first set, and then other five design variables are optimized to get the maximum fuel economy for the specific value of DOH. The results show that the optimal DOH is around 0.653. Compared to the baseline design, the number of fuel cells was increased from 381 to 498, whereas the battery capacity could be decreased from 7.035 to 4.87 Ah. As the DOH increases from 0.2 to 0.6, the fuel economy improves because the fuel cell efficiency increases. When the DOH goes beyond 0.75, the fuel economy drops because decreased battery capacity fails to capture the regenerative braking energy.

5. Conclusion

In this paper, the PCS method which is implemented in ADVISOR environment is utilized to design relevant energy control strategies for FCBHV for the improvement of fuel economy and mileage of continuation of journey. A secondary development for ADVISOR is implemented based on the system architecture of FCBHV. We suggested a comprehensive and systematic framework that makes it possible to optimize power control and component sizing simultaneously for the design of FCBHV. The results indicate that the proposed control strategy can satisfy the power requirement for two standard driving cycles. In two cycle conditions, the PCS for FCBHV has smaller consumption than the PTC for FCBHV. Hence, the proposed strategy will give a novel approach for the advanced energy control system of FCBHV.

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