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Effects of Different Powertrain Configurations and Control Strategies on Fuel Economy of Fuel Cell Vehicles

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Abstract – Fuel cells in conjunction with energy storage such as batteries and ultracapacitors can create high power with fast dynamic response, permit the recovery of regenerative braking energy, and mitigate the stress on the fuel cell stack, and potentially permit downsizing the fuel cell system. In this paper, fuel cell vehicles using different hybridization configurations, energy storage technologies, and power split control strategies were modeled and evaluated. Simulations were performed to address the advantages and disadvantages of each powertrain configuration in terms of the operating conditions of fuel cells and the fuel economy improvement potential. Finally, the fuel cell-battery hybrid vehicle model was used to project fuel economy of future fuel cell vehicles in period 2015-2045. *Copyright Form of EVS25*.

Keywords: fuel cell vehicle, hybrid, battery, ultracapacitor, fuel economy

1. Introduction

To reach long-term goals for deep reductions in transportation-related greenhouse gas emissions, hybrid –electric vehicles, clean diesels, bio-fuels, electric cars – plug-ins and fuel cells will play important roles. Hydrogen fuel cell vehicles are one of the solutions that will be needed to address these challenges. Currently, all the major automakers have small fleets of fuel cell vehicle for demonstration and road testing. Honda Clarity is the only fuel cell vehicle available to the public in Southern California. Since fuel cell vehicles were introduced a decade ago, significant technological improvements have been achieved. Fuel cell passenger vehicles compare favorably with internal combustion engine vehicles: 2-3 times more efficient, comparable range, performance and durability.

In the past decade, various powertrain configurations for fuel cell vehicles have been studied [1-14]. The fuel cell vehicle powertrain consists of three key elements: (1) a fuel cell system that consists of a fuel cell stack, air and hydrogen supply, and water and thermal management system; (2) an energy storage unit that stores the electricity; (3) an electronics unit that controls the power split between the fuel cell and the energy storage unit. Fuel cells in combination with energy storage such as power batteries or ultracapacitors can create high power very efficiently with fast dynamic response, permits the capture of regenerative braking energy, and can mitigate the stress on the fuel cell and potentially permit downsizing the fuel cell system. Different approaches to hybridizing fuel cell system have been developed. It is of interest to simulate and evaluate these different hybridization configurations and to explore and project their potential improvement of fuel economy.

In this paper, fuel cell vehicles with different powertrain configurations are modeled using power assist and load leveling control strategies in section 2. These powertrain configurations are simulated and analyzed over FUDS and US06 cycles in section 3. In section 4, the fuel economy potential for mid-size passenger and compact SUV fuel cell-battery hybrids are projected by using the future fuel cell vehicle parameters.

2. System and vehicle modeling

2.1 Fuel Cell System

Fuel cells without energy storage have relatively slow transient power response primarily due to the slow response of air supply to its cathode. The dynamic fuel cell system model developed at UC Davis was used to investigate the response of fuel cells during load

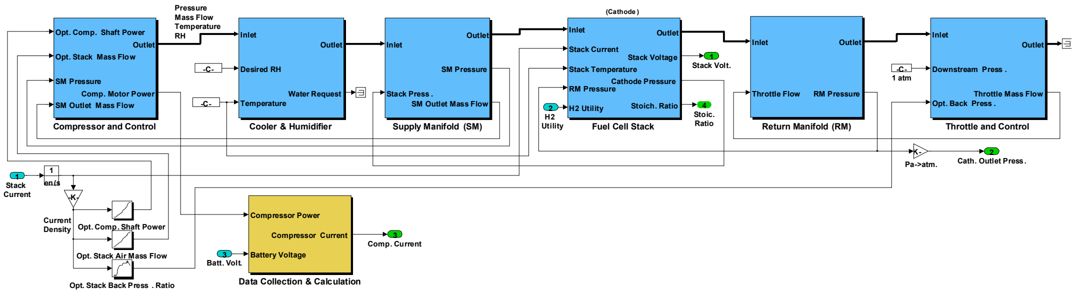


Figure 1 Diagram of the dynamic fuel cell system model (Air supply)

transients [15]. The dynamic air supply system model consists of the compressor and its control, supply manifold, cooler and humidifier, fuel cell stack, return manifold, and throttle and its control. The dynamic model incorporates either fundamental equations, as in the fuel cell stack, or performance based maps, as for the compressor. The model was developed by using Matlab®/Simulink®, as shown in Figure 1. The inputs are the required current and the optimum operating conditions for the fuel cell system and the output is the stack voltage. The rotational speed of the compressor and the pressures in each stage of the air supply system are the state variables. The optimum stoichiometry and back pressure conditions were used in the simulation [16].

2.2 Vehicle modeling

Vehicle performance and fuel economy were calculated using the fuel cell vehicle model. The vehicle model is a forward facing simulator. An illustrative schematic of the Simulink block diagram is shown in Figure 2. The drive cycle block defines the driving profiles. The driver block generates the acceleration and brake commands to the vehicle block according to the drive cycle and the actual vehicle velocity. The vehicle block calculates the vehicle velocity, traction motor power, and the current commands for the fuel cell system and energy storage. The model provides a capability for simulating different vehicle powertrains, control strategies, and dynamics of the fuel cell system and vehicle.

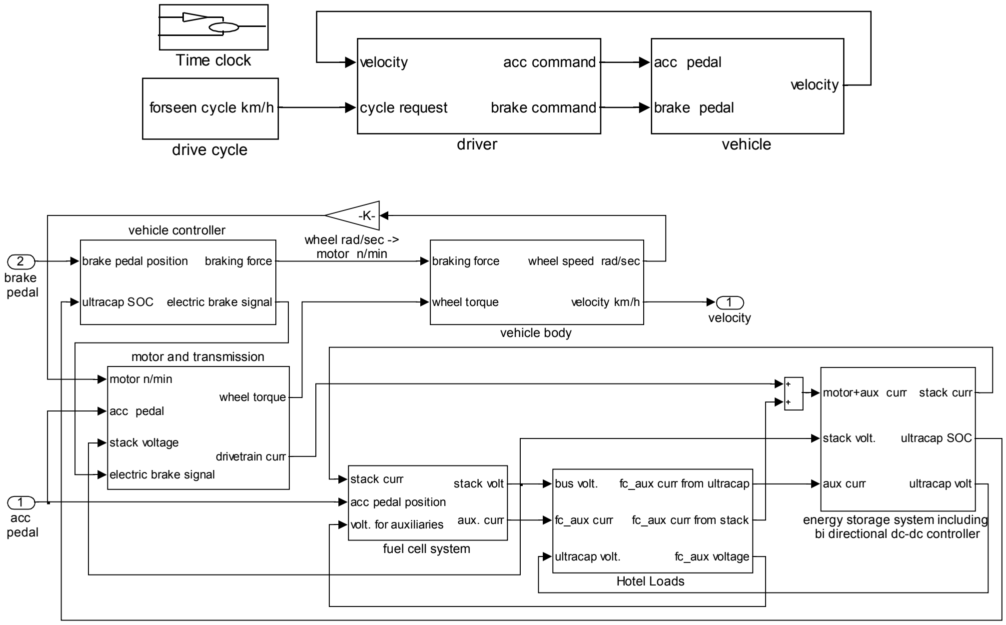
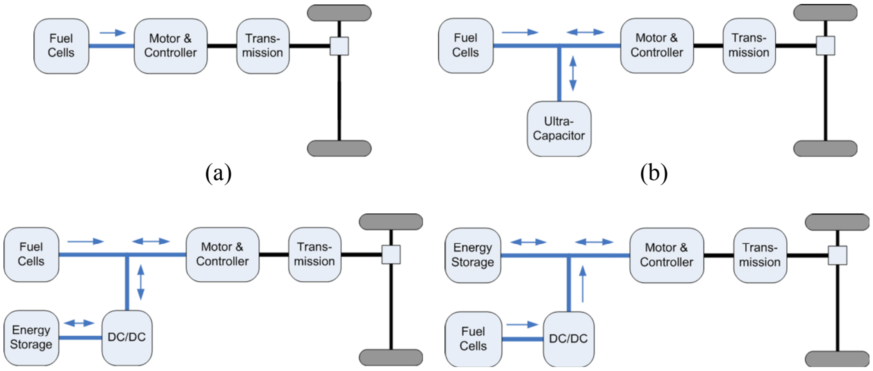


Figure 2: Block diagram for fuel cell vehicle with energy storage coupled with fuel cells via a converter.



(a) (b)

(c) (d)

Figure 3 Powertrain configurations for fuel cell vehicles

2.3 Powertrain Configuration

Considering hybridization of fuel cell vehicles, designers have a number of choices to consider. These alternatives include the physical arrangement of the power sources, selection of the energy storage technology and devices, and the control strategy for splitting power between the fuel cell and the energy storage unit. The study in this paper simulates the following powertrain configurations (shown in Figure 3) and power splitting control strategies.

(a) Direct hydrogen fuel cell vehicles (FCVs) without energy storage. This configuration was used in the first generation fuel cell vehicle and is employed here as the baseline for comparing different powertrain configurations.

(b) FCVs with ultracapacitors directly connected in parallel with fuel cells without interface electronics. The relatively soft voltage-current characteristics of fuel cells allows the ultracapacitors to operate over a fairly wide range of voltage resulting in self regulation of the fuel cell. This configuration is less complex and less costly than a system using electronics.

(c) FCVs with energy storage coupled in parallel with fuel cells through a DC/DC converter. This configuration actively controls the power from the fuel cell using either a load-leveling or power assist strategy. The DC/DC converter can maximize the utilization of energy storage if an ultracapacitor unit is utilized.

(d) FCVs with fuel cells connected to energy storage via a DC/DC converter. The converter regulates the power flow and maintains the DC-link voltage. The converter can maintain relatively steady power from the fuel cell.

2.4 Power splitting strategies

Hybrid powertrains improve the drivetrain efficiency over non-hybrid systems by utilizing energy storage to permit operation of the fuel cell system near its most efficient conditions and by recovering energy during braking that would otherwise be lost in heat. The energy storage is charged during low power demand and discharged during high power demand. The state of charge (SOC) of the energy storage unit can be maintained within a narrow range.

For fuel cell vehicles with ultracapacitors coupled directly in parallel with the fuel cell, a power diode is employed to prevent the flow of reverse current during braking periods. The dc-link voltage depends on the fuel cell terminal voltage. The power sharing between the fuel cell and ultracapacitor is determined by the current-voltage characteristics of fuel cell and ultracapacitor. The current of the ultracapacitors is governed by the differential equation (1).

$$\frac{dV_{cap}}{dt} = \frac{i_{cap}}{C} + R_{cap}\frac{di_{cap}}{dt} \qquad (1)$$

$$V_{cap} = V_{fc} - V_{diode}$$

Fuel cell vehicles with a DC/DC converter placed between the fuel cell and energy storage have more choices for balancing the power flow between the fuel cell and the energy storage. The general control objective is to operate the fuel cell system only in its high efficiency region. Two different control strategies, power-assist and load-leveling, can be employed [15]. Both control strategies maintain the SOC of the energy storage within a specified range. Power assist control splits the current demand of the traction motor i_{motor} based on the fuel cell voltage V_{fc} and the energy storage SOC. If the fuel cell voltage remains relative high, it will provide most of the current to the motor. When the fuel cell voltage becomes low and the energy storage SOC is high, the energy storage unit will provide a large fraction of the current demanded by the motor. The current command for the energy storage device i_{ess} is expressed in equation (2) with the fuel cell providing the remaining current.

$$i_{ess} = f\left(V_{fc}\right) f_{ess}(SOC) i_{motor} \qquad (2)$$

In the load leveling control strategy, the fuel cell provides relatively steady power and the energy storage device provides transient power. The fuel cell current command i_{fc} is averaged over a specified time period such as 60 s.

$$i_{fc} = i_{av,60s} \qquad (3)$$

3. Simulation results

The performance and fuel consumption of mid-size fuel cell vehicles were simulated for the different powertrain configurations and control strategies using the vehicle models discussed in the previous sections. Simulations were performed for the hybrid fuel cell vehicles with a dynamic fuel cell system operating in the optimal varying back pressure mode. The simulation parameters are listed in Table 1.

Test data for an Altairnano 4 Ah lithium titanate oxide cell and an APowerCap carbon/carbon 450 F ultracapacitor obtained from testing at UC Davis were utilized and scaled for the energy storage unit models [17]. The battery SOC swing is limited to be between 0.6 and 0.8. The minimum voltage of the ultracapacitor is set as 50 percent of its rated voltage. The usable SOC ($(V - V_{rated}/2)/(V_{rated}/2)$) is controlled to be between 0.2 and 0.95. A 60s moving average of stack current is used for load leveling the fuel cell in hybrid vehicles with interface electronics. The simulations are performed over the FUDS and US06 cycles. The voltage and current of fuel cell stack for the various cases on the FUDS cycle are plotted in Figures 4 and 5. The corresponding current and SOC of the energy storage units are shown in Figure 6 and 7.

Comparisons of the simulation results indicate that all the powertrain configurations using energy storage significantly load-level the fuel cell operation - that is considerably reduce the maximum current and the voltage and current transient dynamics and thus mitigates the stress on the fuel cell stack. Load leveling also makes downsizing the fuel cell stack possible. Either the high power, lithium titanate battery or the ultracapacitor can be used for load leveling. The magnitude of the voltage and current fluctuations are somewhat less using the battery. As would be expected, the variation of the SOC of the ultracapacitor in Figure 7 shows that with interface electronics the ultracapacitor can utilize a large fraction of the energy stored.

Table 1 Vehicle simulation parameters

Vehicle and System Parameters	
Drag Coefficient	0.3
Frontal Area (m2)	2.2
Rolling Resistance	0.01
Vehicle Hotel Load (kW)	0.3
Vehicle Mass without energy storage (kg) *	1500
Electric Motor (kW)	75
Fuel Cell Stack and Auxiliaries	
Max. Net Power (kW)	87.6
Gross Power (kW)	106
Number of Cells	440
Cell Area (cm2)	510
Compressor (kW)	17.2
Energy Storages	
Ultracapacitor Capacity (Wh)	120
Ultracapacitor Module No. in Series	160**
Li-ion Battery Capacity (kWh)	0.8
Li-ion Battery Module No. in Series	144

* Vehicle mass recalculated based on the size and type of energy storage

** 148 is for the case with ultracapacitors connected without interface electronics

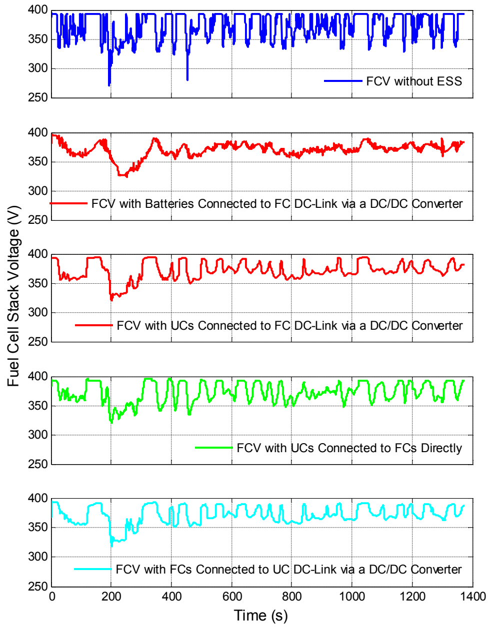


Figure 4 Comparison of the fuel cell stack voltage

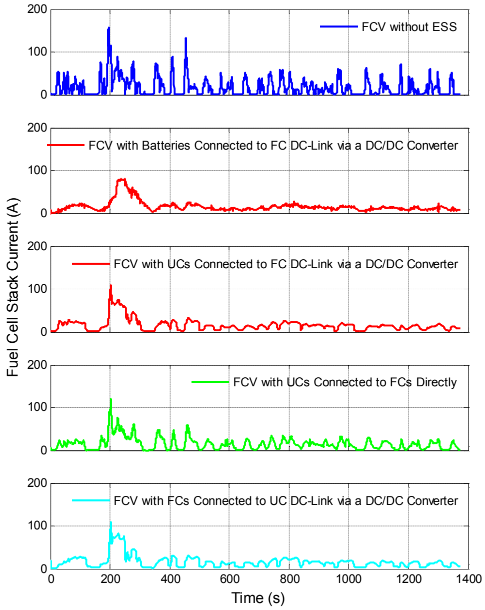


Figure 5 Comparison of the fuel cell current

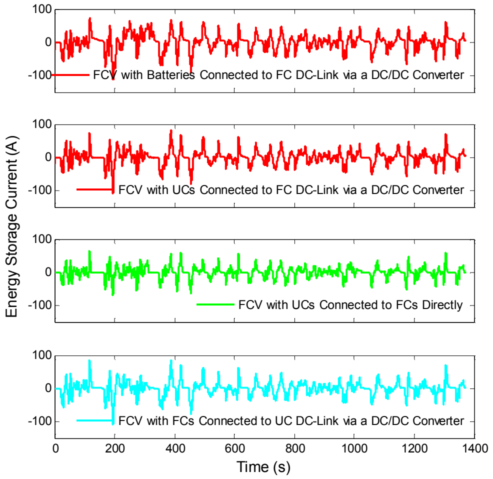


Figure 6 Comparison of the energy storage current

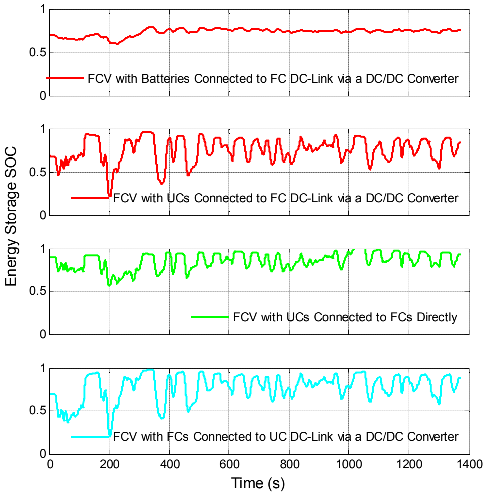


Figure 7 Comparison of the energy storage SOC

The effect of the power assist and load leveling control strategies on fuel operation and vehicle fuel economy with interface electronics on the FUDS and US06 driving cycles were also studied. Figure 8 shows the fuel cell and battery currents for the power assist and load leveling strategies over the US06 cycle. Compared to power assist strategy, load leveling control mitigates to a greater extent the load fluctuations on the fuel cell which results less stress on the fuel cell stack. However, for this strategy a significant fraction of the power/energy passes through the DC/DC converter for charging and discharging the energy storage, which leads to significant losses in the electronics. Figure 9 and Figure 10 show the fuel economy improvements for fuel cell vehicles with different sizes of batteries and ultracapacitors coupled to the fuel cell dc-link via a DC/DC converter. The improvements in fuel economy

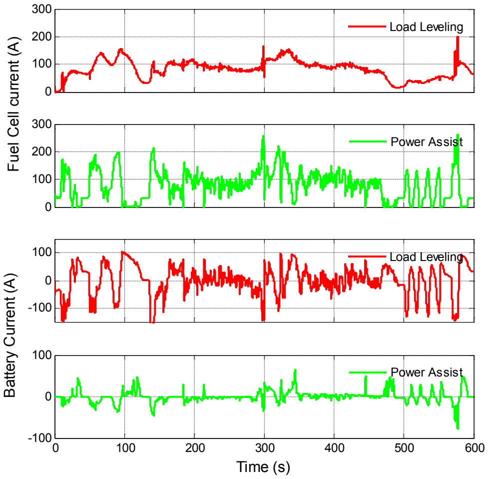


Figure 8 Comparison of load leveling and power assist control over the US06 cycle (Altairnano 800Wh Battery)

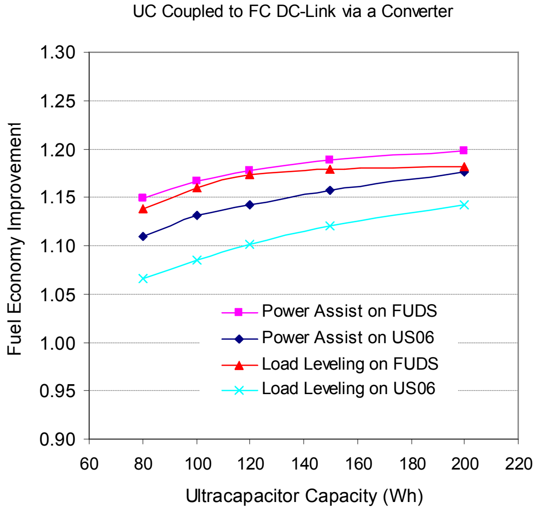


Figure 9 Comparison of fuel cell-ultracapacitor hybrids with load leveling (60sec) and power assist control over the FUDS and US06 cycles

(that is hydrogen consumption) are relatively small being in the range of 5-15% with the improvements being larger for the FUDS cycle than for the US06 cycle. Compared to the load leveling strategy, power assist strategy results in a larger improvements in fuel economy due to lower losses in the interface electronics and energy storage units. The fuel economy improvements are greater using ultracapacitors than batteries on both driving cycles. In addition, the effect of the control strategy on the fuel economy improvement is considerably less using ultracapacitors than batteries. For both energy storage technologies, the improvement increases as the size of the energy storage unit is increased.

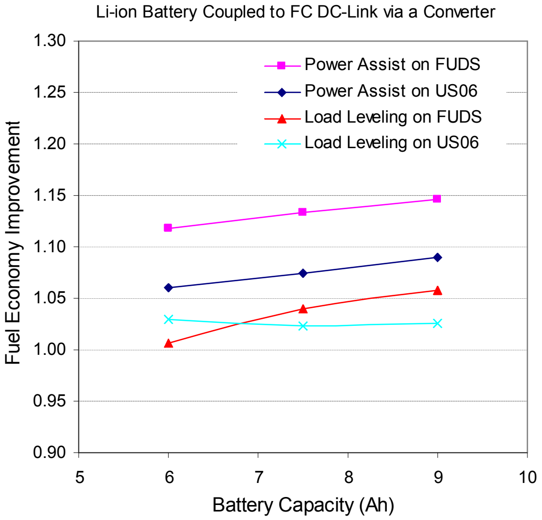


Figure 10 Comparison of fuel cell-battery hybrids with load leveling (60sec) and power assist control over the FUDS and US06 cycles

The fuel cell vehicle simulation results indicate that utilizing carbon/carbon ultracapacitors coupled via a DC/DC converter using the load leveling control strategy is the best approach for improving fuel economy and mitigating the stress on the fuel cell.

4. Fuel economy projections (2015-2045)

Simulations were also performed for projecting the fuel economy of fuel cell-battery hybrid vehicles in the years 2015, 2030 and 2045. The vehicle parameters used in the previous DOE study [18] were used in the present projections. The cathode/anode overpotential in the UCD fuel cell model was scaled to match the DOE projection for peak efficiency of the fuel cell system. Simulations were run for both the power assist and load leveling control strategies on the FUDS, HWY, and US06 drive cycles for mid-size passenger cars and compact SUVs. The simulation parameters and the averaged fuel economy of the UCD projections and the DOE values [18] are given in Table 2. The UCD simulation results are close to the DOE projections for both the passenger car and SUV. Both projections indicate high fuel economies for fuel cell vehicles which are 2-3 times those of vehicles current available in 2010.

Table 2 Fuel economy projection for fuel cell-battery hybrid vehicles

Mid-Size Passenger Cars

	2015		2030		2045	
	UCD*	DOE	UCD	DOE	UCD	DOE
UDDS	82.6	70	102.8	102	108.9	114
HWY	90.8	79	111.5	114	119.5	130
US06	61.3	--	76.2	--	82.3	--

Vehicle Configuration	2015	2030	2045
C_D	.25	.22	.2
A_F (m^2)	2.2	2.2	2.2
Fr	.007	.006	.006
FC (kW)	83.2	76.6	72.1
Motor (kW)	103	100	99
Battery (kWh)	.93	.85	.85
Vehicle Test Weight (kg)	1516	1383	1366
Elec. Acc Load (W)	220	240	260

Compact SUVs

	2015		2030		2045	
	UCD	DOE	UCD	DOE	UCD	DOE
UDDS	61.2	62	74.7	73	80.8	82
HWY	60.6	59	73.0	68	78.7	77
US06	40.5	--	48.8	--	52.9	--

Vehicle Configuration	2015	2030	2045
C_D	.37	.35	.33
A_F (m^2)	2.9	2.94	2.94
Fr	.0075	.007	.007
FC (kW)	102.6	95.4	92.6
Motor (kW)	129	110	116
Batter (kWh)	1.15	1.05	1.05
Vehicle Test Weight (kg)	1875	1705	1683
Elec. Acc Load (W)	250	250	250

5. Summary and Conclusion

Fuel cell vehicles using different hybridization configurations, energy storage technologies, and power split control strategies were modeled and evaluated. Comparisons of the simulation results indicate that all the powertrain configurations using energy storage significantly load-level the fuel cell operation - that is considerably reduce the maximum current and the voltage and current transient dynamics and thus mitigate the stress on the fuel cell stack. Either the high power, lithium titanate battery or the ultracapacitor can be used for load leveling. The magnitude of the voltage and current fluctuations are somewhat less using the battery. As would be expected, the variation of the SOC of the ultracapacitor shows that with interface electronics the ultracapacitor can utilize a large fraction of the energy stored.

The effect of the power assist and load leveling control strategies on vehicle fuel economy with interface electronics on the FUDS and US06 driving cycles were also studied. The improvements in fuel economy (that is hydrogen consumption) are relatively small being in the range of 5-15% with the improvements being larger for the FUDS cycle than for the US06 cycle. Compared to the load leveling strategy, power assist strategy results in a larger improvements in fuel economy due to lower losses in the interface electronics and energy storage units. The fuel economy improvements are greater using ultracapacitors than batteries on both driving cycles. In addition, the effect of the control strategy on the fuel economy improvement is considerably less using ultracapacitors than batteries. For both energy storage technologies, the improvement increases as the size of the energy storage unit is increased.

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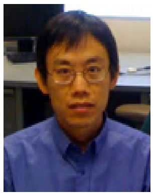

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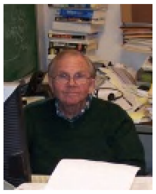

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