An Improved Powertrain Topology for Fuel Cell-Battery-Ultracapacitor Vehicles

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Abstract— **A combined battery-ultracapacitor energy storage system is a promising possibility for use with fuel cell vehicles because it combines the advantages of batteries and ultracapacitors. This paper reviews some popular topologies for fuel cell-battery-ultracapacitor powertrains, and presents a new topology which minimizes many of the disadvantages of the other topologies. Simulation results for the new topology are presented and are compared to results for a common fuel cell-battery-ultracapacitor topology. The new topology is shown to improve the fuel economy and reduce the cost of the vehicle.**

I. INTRODUCTION

Factors such as dwindling fossil fuel reserves, energy security concerns, and increased global warming combine to indicate that a replacement for the internal combustion engine (ICE) vehicle is needed. Fuel cell vehicles have the potential to address these problems surrounding the ICE vehicle. While most major automotive companies are investing in the commercialization of fuel cell vehicles [1], many challenges remain in getting fuel cell vehicles on the road: increasing fuel cell and battery reliability, developing a hydrogen infrastructure, and reducing the vehicle cost [2][3]. Thus, the design challenge is to choose the powertrain component types and sizes that, in combination with an appropriate control strategy, create a vehicle which maximizes fuel economy, reliability, and performance, and minimizes cost.

A hybrid fuel cell vehicle contains an energy storage system (ESS) to provide peak power and capture regenerative braking energy. The ESS is usually a battery module, an ultracapacitor module, or a combination of both [4]-[6]. Batteries have higher specific energy than ultracapacitors, and can hence provide extra power for a longer period of time [5][6]. Ultracapacitors generally have a higher specific power than batteries, are more efficient, and have a longer lifetime in terms of number of charge/discharge cycles [5][6].

Recent studies [7]-[11] have shown that the combined battery-ultracapacitor ESS can provide excellent performance and fuel economy. Thus, this paper focuses on the development of improved fuel cell-battery-ultracapacitor (FC-B-UC) powertrain topologies. First, a literature review is performed to analyze the advantages and disadvantages of a number of common topologies. Then a novel topology is presented which minimizes many of the disadvantages of existing topologies. Simulation results based on the vehicle simulator built in MATLAB/Simulink and presented in [11] are given, and are compared to the optimal fuel cell-battery-ultracapacitor results from [11]. The simulation framework developed in [11] is unique because it includes detailed modeling of DC/DC converters, varies a control parameter to better identify optimal configurations, and includes accurate costs of all powertrain components.

II. ANALYSIS OF FC-B-UC TOPOLOGIES

This section analyzes four FC-B-UC topologies, shown in Fig. 1, found in the literature. In general, the fuel cell is usually connected to the high-voltage bus through a DC/DC converter, so that the fuel cell power can be controlled and the fuel cell voltage can be stepped-up or stepped-down to match the voltage range of the inverter. All of the topologies shown in Fig. 1 use a DC/DC boost converter after the fuel cell, which is generally advantageous compared to a buck

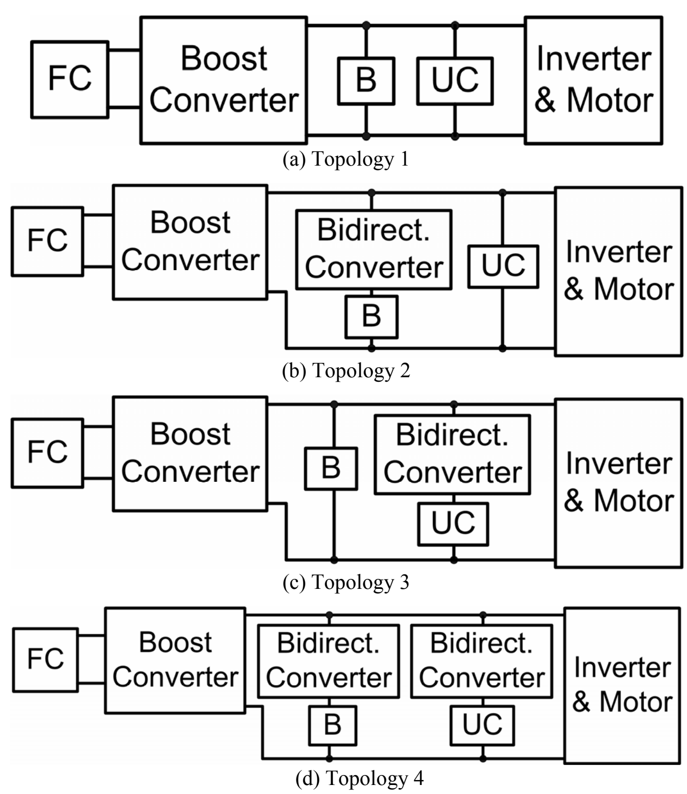

Fig. 1. Fuel cell-battery-ultracapacitor vehicle topologies

converter for the following reason: it is more efficient to operate the inverter and motor at high-voltage/low-current rather than low-voltage/high-current so that I^2R losses are minimized for a given output power. However, the optimal fuel cell size for a given vehicle, in terms of output power, usually has a lower voltage than the inverter. Thus, using a boost converter allows a smaller and less expensive fuel cell to be chosen, since the fuel cell voltage can be stepped-up to match the higher inverter voltage. This is an important cost-reduction strategy since the fuel cell is currently the most expensive source of power in the vehicle.

The parallel battery-ultracapacitor connection shown in Fig. 1(a) (Topology 1) has been analyzed in [12]. Since both the battery and ultracapacitor are directly connected to the high voltage bus, this topology does not have the extra mass, cost, and losses of the additional DC/DC converter(s) associated with other topologies. Since high power (20kW – 70kW) DC/DC converters add significant mass and cost to the powertrain, this is a large savings for this topology. However, a major disadvantage of this topology is that the power sharing between the battery and the ultracapacitor is determined by their respective impedances. That is, there is no mechanism to separate or control the power flow of each component, so when current flows from the combined ESS, it always flows from both components. A major motivation for combining batteries and ultracapacitors is to extend the battery lifetime by allowing the ultracapacitor (which has a much longer lifetime in terms of charge and discharge cycles [13][14]) to provide more of the ESS power requirements. Thus, for the power request profiles typical of a fuel cell vehicle ESS, this topology generally fails in accomplishing the goal of significantly reducing the battery current.

The topology shown in Fig. 1(b) (Topology 2) [15] corrects the main problem with Topology 1 because the bidirectional DC/DC converter between the battery and the high voltage bus allows independent control of the battery power. This converter also allows indirect control over the ultracapacitor power, since it is the difference between the power required at the motor inverter and the total power provided by the fuel cell and battery. The disadvantage of this topology is the additional mass, cost, and losses associated with the DC/DC converter connected to the battery, which can be significant. Another potential problem with this topology relates to the efficiency of charging the battery. High-power DC/DC converters are usually relatively inefficient when they are operated at very low load. However, charging the battery is relatively inefficient at high currents due to the I^2R losses associated with the battery's internal resistance. In addition, when charging the battery from the fuel cell, the power must flow through 2 DC/DC converters to reach the battery, which introduces further losses. Thus, Topology 2 does not present any options to charge the battery at relatively high efficiencies.

Topology 3 shown in Fig. 1(c) [16], uses the same principle as in Topology 2 by connecting one ESS component, the ultracapacitor in this case, to the high voltage bus through a bidirectional DC/DC converter. Thus, it also gives the advantage of full control of the power from each ESS component and the disadvantage of the extra mass, cost, and losses of the extra DC/DC converter. The choice between Topology 2 and Topology 3 may depend on the size of the battery and ultracapacitor in the proposed design: using the DC/DC converter with the component having lower power rating means the DC/DC converter size and cost can be minimized. However, considering the desired operation of the combined ESS presents another strategy for choosing the superior topology. When the control of the ESS power is considered, it is clear that the ultracapacitor will be used more often to provide fast and large power transients – this control strategy accomplishes the goal of increasing the battery lifetime by using the battery less often. Thus, from this point of view, it would be best to use the bidirectional DC/DC converter with the battery, because the efficiency losses of the DC/DC converter will be minimized since the battery operates much less often than the ultracapacitor. However, this must be weighed against the gains in efficiency that could be achieved with Topology 3 since higher-efficiency battery charging may be possible.

Topology 4, shown in Fig. 1(d) [7][8] has bidirectional DC/DC converters connected to both the battery and the ultracapacitor. This adds significant mass, cost, and losses to the system. Also, a capacitor must be added to the high voltage bus to provide slack [7], since all four of the components connected to the high voltage bus (three DC/DC converters and the motor inverter) are directly controlled. Topology 4 is generally undesirable compared to Topology 2 or 3 due to the extra converters with no significant benefit.

III. New FC-B-UC Topology

A. Proposed Topology

A new topology for fuel cell-battery-ultracapacitor powertrains is presented in Fig. 2. This topology aims to correct the disadvantages of the previously discussed Topology 2 and Topology 3, while adding no significant disadvantages. The topology only requires one high-power DC/DC unidirectional converter for boosting the fuel cell voltage. The ultracapacitor is connected directly to the high voltage bus and the battery is connected to the high voltage bus through a diode. Because this diode is not used in a switching scheme, it does not have to be a fast-recovery diode, and hence it can have a very low forward voltage drop.

The theory of operation is as follows: when power is required from the ESS, the ultracapacitor provides the initial power until the ultracapacitor voltage reaches the battery terminal voltage (minus the diode forward voltage drop, approximately 0.7V). At this point, the battery and the ultracapacitor both provide the required power, and their respective impedances determine the power sharing, similar to the operation of Topology 1. When regenerative braking occurs, the ultracapacitor is charged back up to a higher voltage than the battery. This operation ensures that the ultracapacitor provides more of the transient power requests, while the battery is only used when the power request is very large or the ultracapacitor is depleted.

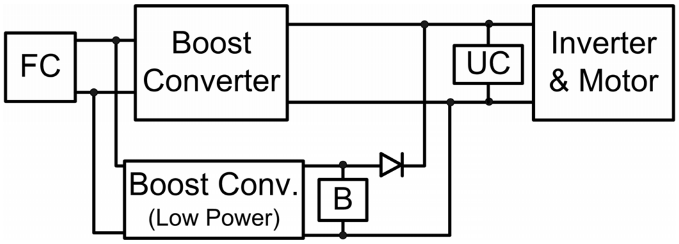

Fig. 2. Proposed fuel cell-battery-ultracapacitor powertrain topology

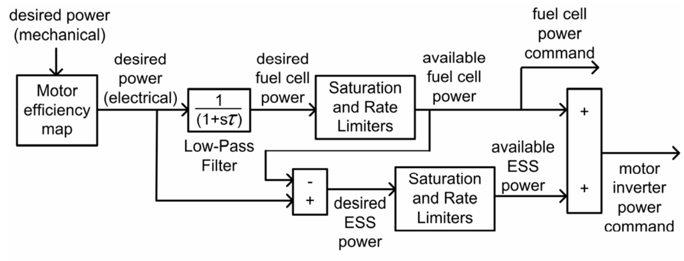

Fig. 3. Block diagram of control strategy for the proposed topology

The battery can be trickle-charged from the fuel cell through a low power unidirectional boost converter. Thus, very high efficiency charging of the battery can be achieved, since the boost converter can operate in its high efficiency region, yet provide low-power charging for the battery (e.g. 1kW) to minimize the I^2R losses in the battery.

In summary, the proposed topology has the following advantages:

- It uses one low-power (e.g. 1kW) DC/DC converter instead of the high-power (20kW-70kW) bidirectional DC/DC converter used in Topology 2 and Topology 3. The mass and cost savings caused by this difference are significant.
- It provides a higher efficiency path for discharging the battery, since the losses from a low-V_F diode are less than those of a bidirectional DC/DC converter.
- It provides a high-efficiency path for charging the battery, since the power is only processed by one DC/DC converter and high efficiency low-power charging is possible.
- The design ensures that the ultracapacitor fulfills more of the transient power requests, thus reducing battery use and extending battery lifetime.

The proposed topology does not accept regenerative braking energy into the battery due to the presence of the diode. This disadvantage can be minimized by appropriately sizing the ultracapacitor and battery so that all or the majority of the regenerative braking energy is stored.

B. *Control Strategy for Proposed Topology*

The proposed topology is unique because the power sharing between the battery and the ultracapacitor is dependent on the sizes of the battery and the ultracapacitor. A larger capacitance will mean a slower fall of the ultracapacitor voltage, which determines when the battery starts conducting. Also, a higher-voltage battery will start conducting sooner than a lower-voltage battery. Basically, the control of the ESS power split is embedded in the design of the components. Thus, the vehicle simulation is run numerous times for different sizes of batteries and ultracapacitors so that the best results can be extracted.

The topology has only two control inputs: the fuel cell power command to the high-power DC/DC converter and the motor inverter power command to the inverter. Fig. 3 shows a simplified diagram of the control strategy for positive power.

The overall power request is split into fuel cell requested power and ESS requested power. A low-pass filter, with time constant τ, is used to split the power. This control variable is also varied in the simulations to ensure the optimal control is obtained for each vehicle plant. When the desired electrical power is below a certain level (i.e., 4kW), the "Saturation and Rate Limiters" block on the fuel cell power request sets the available fuel cell power to zero, so that the ESS provides all of the required power. This functionality prevents the fuel cell from operating at very low power, in its low-efficiency region.

When the required power is negative, the ultracapacitor accepts the regenerative braking energy up to its current limit while its voltage is below the maximum bus voltage. Beyond this point, mechanical braking is used.

The battery charging strategy helps to ensure that the battery never becomes depleted, as it is often being trickle-charged. The battery is charged from the fuel cell at a constant 1kW when the following conditions are met:

1) The battery is not providing power to the motor.
2) The fuel cell is operating in a high-efficiency region.
3) The battery state of charge is less than 99%.

IV. Simulation Results

The MATLAB/Simulink vehicle simulator and variables used in this study are the same as those presented in [11]. As in [11], the battery cells are modeled after A123 Systems' new lithium-ion cell [13] and the ultracapacitor cells are modeled after Maxwell Ultracapacitor's 350F cell [14]. Thus, the results from the proposed topology can be compared to the results for the fuel cell-battery-ultracapacitor topology (Topology 2) simulated in [11].

The vehicle completes the first 505 seconds of the Federal Urban Driving Schedule (FUDS), shown in Fig. 4 [17], to obtain the vehicle fuel economy in mpgge (miles per gallon gasoline equivalent). Numerous plant variables and one control variable are varied in the parametric study, as shown in Table 1. Since the high-voltage bus range is fixed (250V - 400V), the number of ultracapacitor cells in series is fixed so that when fully charged, the ultracapacitor voltage is 400V.

A. *Verification of Operation*

The simulations show that the proposed topology is able to accurately follow the given drive cycle, while ensuring that the ultracapacitor provides more of the ESS transient power.

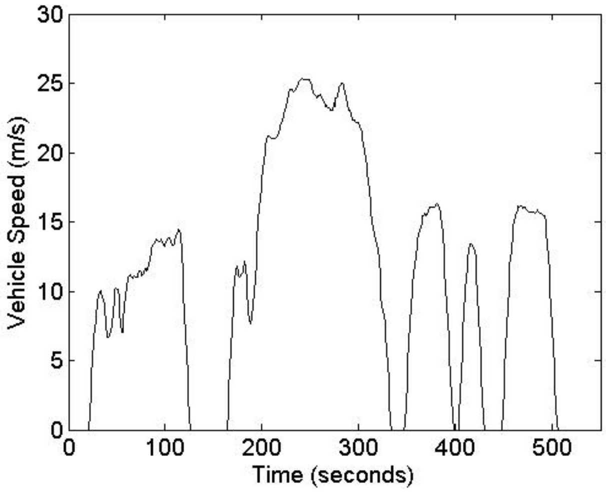

Fig. 4. First 505 seconds of the Federal Urban Driving Schedule [17]

TABLE 1. PARAMETRIC STUDY VARIABLES AND BOUNDS

Variable	Lower Bound	Step Size	Upper Bound
Number of battery cells in series (batt_s)	80	5	105
Number of battery strings in parallel (batt_p)	2	1	5
Number of ultracapacitor strings in parallel (uc_p)	2	1	6
Time constant for filter (τ)	10	2	18

The ultracapacitor and battery currents are shown in Fig. 5 for the FUDS (*batt_p* = 3, *batt_s* = 85, *uc_p* = 5). It can be seen that the ultracapacitor provides the majority of the transient power. Also, the battery is being trickle-charged by the fuel cell most of the time. Fig. 6 shows the ultracapacitor and battery voltages for the same cycle.

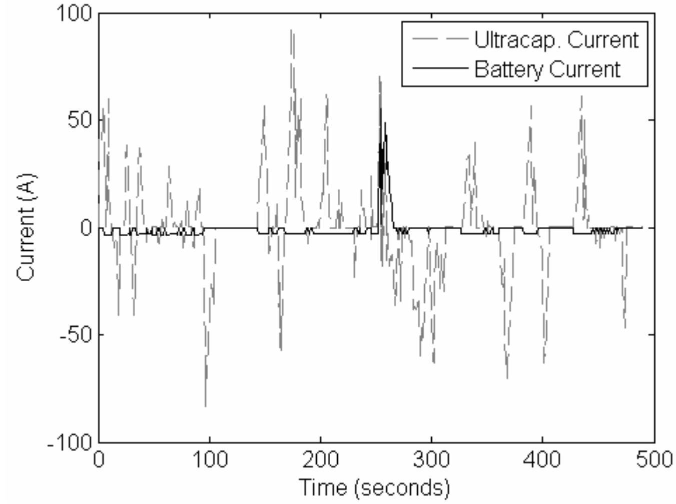

Fig. 5. Ultracapacitor and battery current of the proposed topology

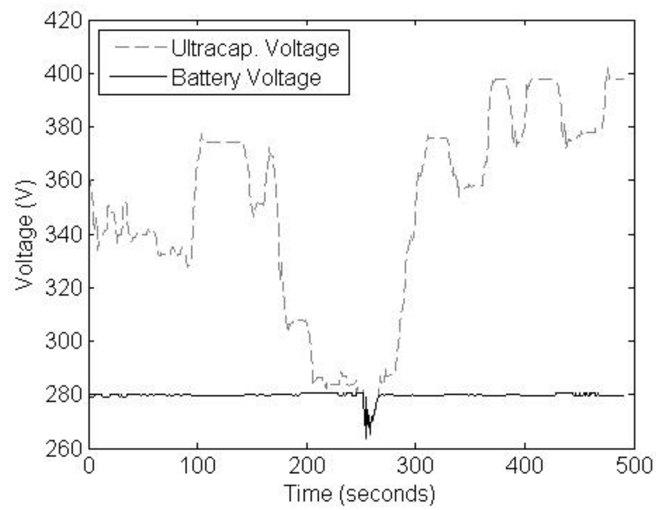

Fig. 6. Ultracapacitor and battery voltage of the proposed topology

B. Analysis of Results

The results from [11] showed that regardless of the ESS type, the optimal fuel cell size for the GM Equinox model (for the given objective function in [11]) was about 40kW. Thus, the fuel cell size has been kept constant at 40kW for this study.

In [11], it was also found that better fuel economy was achieved when the battery voltage was relatively high for Topology 2. This is due to the fact that for the same amount of battery power, higher voltage means lower battery current, and less I^2R losses in the battery and bidirectional DC/DC converter. Thus, for the study of Topology 2 in [11], the number of battery cells in series, *batt_s*, was set to 75, as this was the highest voltage allowed while still being lower than the high voltage bus (250V – 400V), since a simple 2-quadrant bidirectional converter was used.

In the present optimization study for the proposed fuel cell-battery-ultracapacitor topology, the minimum lower bound for *batt_s* is set to 80 so that the battery voltage is higher than the minimum bus voltage, and hence the battery will likely conduct at some point in the drive cycle. The simulation results show that for the proposed topology, higher fuel economy is achieved when the number of battery cells in series is 80, or as low as possible. This is due to the fact that a lower-voltage battery will conduct less often (since the diode will less often become forward-biased) and hence the higher-efficiency ultracapacitor will provide more of the power transients. Also, a lower voltage battery will allow the ultracapacitor voltage to drop lower during acceleration, leaving more room in the ultracapacitor to store regenerative braking energy when the vehicle next brakes.

A comparison of the ESS mass, ESS cost, and overall vehicle fuel economy between Topology 2 and the proposed topology is performed. Figs. 7-9 show the results. To facilitate a fair comparison, the numbers of battery and ultracapacitor strings in parallel are kept constant while comparing the topologies. Fig. 7 shows that even though 5 more battery cells are used in series for each battery string in the proposed topology compared to topology 2 (80 cells in series versus 75 cells in series), the total ESS mass is still reduced for the new topology, as expected. This is due to the fact that the sum of the masses of the extra battery cells, the 1kW boost converter, and the diode, is less than the mass of the high-power DC/DC converter (52kW – 87kW depending on *batt_p*) in Topology 2.

Fig. 8 shows the comparison of costs of the ESSs in Topology 2 and the proposed topology. Again, the cost of the additional battery cells, 1kW boost converter, and diode in the proposed topology is less than the cost of the high-power bidirectional DC/DC converter used with the battery in Topology 2. Thus, the use of the proposed topology reduces the overall cost of the ESS.

Fig. 9 shows the comparison of overall fuel economies for topology 2 and the proposed topology. It can be seen that the proposed topology significantly increases the fuel economy for the ESS sizes shown. This can be attributed to three factors:

- Reduced losses in the battery diode compared to the losses in the bidirectional DC/DC converter in Topology 2
- Higher-efficiency battery charging path
- Lower overall vehicle mass (less power is required to follow the same drive cycle)

It was found, however, that the improvement in fuel economy gets smaller as the number of ultracapacitor strings in parallel is reduced. This is because the voltage of a lower-capacitance ultracapacitor falls more quickly for a given power profile, and hence the battery will conduct more often. The battery has more internal I^2R losses than the ultracapacitor and there are also some losses in the battery diode. This explains why the fuel economy gains are not as significant for smaller ultracapacitors. This observation highlights the need for optimal design of the battery and ultracapacitor in the proposed topology, as the battery voltage and ultracapacitor capacitance have a major effect on the operation and efficiency of the proposed combined ESS.

Overall, the simulation results have shown that the objectives of the proposed topology have been achieved: reduced ESS mass, reduced ESS cost, and improved vehicle fuel economy. Furthermore, Fig. 5 shows that with proper design of the battery and ultracapacitor, the battery current can be minimized, thus extending the lifetime of the battery.

V. Conclusions and Future Work

This paper has provided a review of existing fuel cell-battery-ultracapacitor powertrain topologies. The advantages and disadvantages of each topology were discussed, with a focus on low cost, high efficiency, and battery life extension. A new fuel cell-battery-ultracapacitor powertrain topology was proposed to improve upon the main disadvantages of the best existing topologies. Specifically, the high-power bidirectional DC/DC converter used in Topology 2 and Topology 3 was replaced by a low-power boost converter and a diode in the proposed topology. The proposed topology provides a high- efficiency battery charge and discharge path. The battery current can still be minimized through proper design, allowing battery life extension (similar to Topology 2 and 3). Simulation results show that the proposed topology reduces the mass and cost of the ESS while improving the overall vehicle fuel economy due to its efficient design.

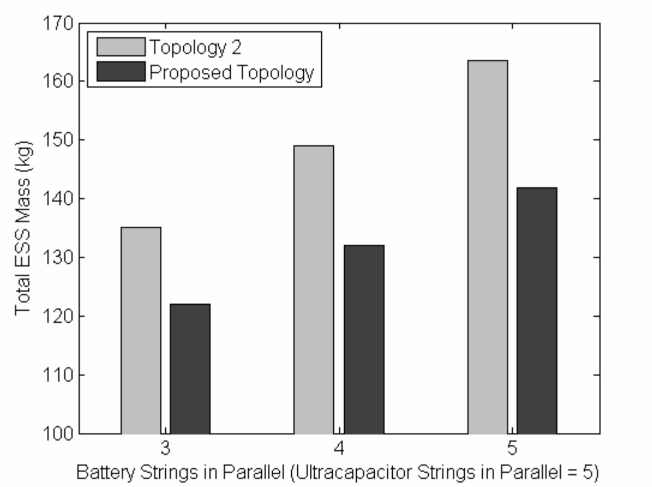

Fig. 7. Comparison of ESS mass for topology 2 and the proposed topology

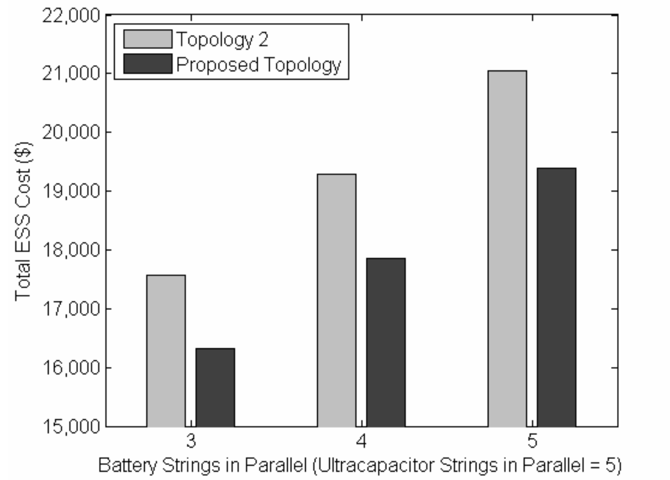

Fig. 8. Comparison of ESS cost for topology 2 and the proposed topology

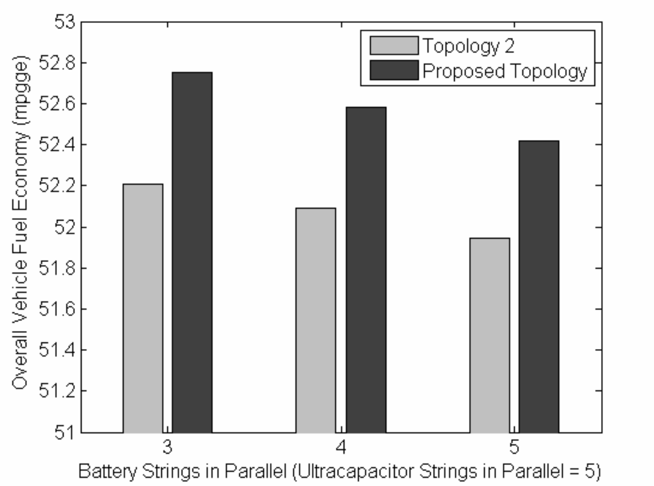

Fig. 9. Comparison of overall vehicle fuel economy for topology 2 and the proposed topology

Future work includes further investigation into the optimal design of the battery and ultracapacitor for the proposed topology. Specifically, since the design of the components essentially dictates the operation of the ESS, future work will include an analytical optimization method for the proposed topology.

References

[1] Fuel Cells 2000, "Fuel Cell Light Duty Vehicles": http://www.fuelcells.org/info/charts.html

[2] R. Rose, "Questions and Answers About Hydrogen and Fuel Cells" (Report style), 2005, Washington, DC: U.S. Dept. of Energy.

[3] S. Williamson and A. Emadi, "Comparative assessment of hybrid electric and fuel cell vehicles based on comprehensive well-to-wheels efficiency analysis", *IEEE Trans. Veh. Technol.*, vol. 54, no. 3, May 2005, pp. 856-862.

[4] A. Emadi, K. Rajashekara, S. Willisamson, S. Lukic, "Topological overview of hybrid electric and fuel cell vehicular power system architectures and configurations", *IEEE Trans. Veh. Technol.*, vol. 54, no. 3, May 2005, pp.763-770.

[5] J. Marshall and M. Kazerani, "Design of an efficient fuel cell vehicle drivetrain, featuring a novel boost converter", in *Proc. of 2005 IEEE Industrial Electronics Conference*, Raleigh, Nov. 6-10, 2005.

[6] A. Burke, "Batteries and ultracapacitors for electric, hybrid, and fuel cell vehicles", in *Proc. of the IEEE*, vol. 95, issue 4, April 2007, pp. 806-820.

[7] R. Schupbach and J. Balda, "The role of ultracapacitors in an energy storage unit for vehicle power management", in *Proc. of 2003 IEEE Vehicular Technology Conference,* Orlando, 2003, pp. 3236-3240.

[8] W. Gao, "Performance comparison of a fuel cell-battery hybrid powertrain and a fuel cell-ultracapacitor hybrid powertrain", *IEEE Trans. Veh. Technol.*, vol. 54, no.3, May 2005, pp. 846-855.

[9] G. Pede, A. Iacobazzi, S. Passerini, A. Bobbio, and G. Botto, "FC vehicle hybridisation: an affordable solution for an energy-efficient FC powered drive train", *Journal of Power Sources*, vol. 125, 2004, pp. 280-291.

[10] A. Baisden and A. Emadi, "ADVISOR-based model of a battery and an ultra-capacitor energy source for hybrid electric vehicles", *IEEE Trans. Veh. Technol.*, vol. 53, no. 1, Jan. 2004, pp. 199-205.

[11] J. Bauman and M. Kazerani, **"**A comparative study of fuel cell-battery, fuel cell-ultracapacitor, and fuel cell-battery-ultracapacitor vehicles", *IEEE Trans. on Veh. Technol.*, accepted for future publication, 2008.

[12] R.A. Dougal, S. Liu, and R.E. White, "Power and life extension of battery-ultracapacitor hybrids", *IEEE Trans. on Components and Packaging Technologies*, vol. 25, no. 1, March 2002, pp. 120-131.

[13] A123 Systems: http://www.a123systems.com

[14] Maxwell Ultracapacitors: http://www.maxwell.com

[15] L. Gao, R.A. Dougal, and S. Liu, "Power enhancement of an actively controlled batter/ultracapacitor hybrid", *IEEE Trans. on Power Electronics*, vol 20, no. 1, Jan. 2005, pp. 236-243.

[16] M.J. Gielniak and Z.J. Shen, "Power management strategy based on game theory for fuel cell hybrid electric vehicles", *IEEE Vehicular Technology Conference,* vol. 6, Sept. 26-29, 2004, pp. 4422-2226.

[17] PSAT (Powrtrain System Analysis Toolkit), Argonne National Lab: http://www.transportation.anl.gove/software/PSAT/index.html