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Contents

Summary

This assessment seeks to evaluate considerations for vehicle power electronics for three possible system configurations of hybrid and fuel cell automobiles. It seeks to identify the relevant state of the art, then discusses a set of research efforts needed to advance the state of power electronics for hybrid and fuel cell vehicles. A dynamic system simulator is discussed and used to prepare sample analyses. Reference vehicle parameters, based on present capabilities of typical U.S. cars, are prepared. Power electronics ratings and system arrangements are presented for three system configurations that follow the reference parameters. The system configurations are:

- A series hybrid electric vehicle with complete electric traction drive and a battery set of about 300 V nominal. This vehicle uses a small engine-generator set as its primary energy source.
- A fuel cell vehicle in which a 48 V fuel cell stack is applied. This vehicle is evaluated both with a battery pack for energy storage and with an ultracapacitor set.
- A fuel cell vehicle in which a 300 V fuel cell stack is applied. This is also evaluated with a battery pack and with an ultracapacitor.

Among these configurations, the 300 V fuel cell system reduces the complexity of the power electronics, and most likely provides cost advantages from a power electronics viewpoint. Cost considerations and general cost guidelines are provided.

The state of the art in terms of power semiconductor devices, materials, and electric machines is evaluated. Critical research needs are discussed. These include low-cost semiconductor packages, understanding of dynamic electrical issues in fuel cell stack operation, improved power converter methods and controls, and others. It is shown that traction drives can be enhanced if simple multi-speed gearboxes can be made available and integrated with electric machines. Subsystem integration is also an important area of future need.

Dynamic Simulation

Previous work on hybrid electric vehicle system simulation includes the ADVISOR program developed through the National Renewable Energy Laboratory (NREL) [1] and a Simulink-based dynamic tool [2]. The ADVISOR program uses static maps of internal subsystems to establish conversion efficiencies and operating characteristics. With this arrangement, it supports long-term analysis over extended drive cycles, and yields results suitable for architectural decisions and high-level operating strategies [3]. In contrast, a dynamic simulation tool is needed to make lower-level comparisons among device types or to provide information for more detailed engineering decisions. The tool introduced in [2] is less well suited for long-term drive cycle comparisons, since it models operation on microsecond time scales. However, an assessment of power electronics ratings and requirements requires a dynamic tool, since details of losses and device behavior require low-level modelling.

One key task of this power electronics assessment project has been to extend dynamic simulation to fuel cells and ultracapacitors. Since fuel cells respond on multiple second time scales (or more) while ultracapacitors can respond in milliseconds (or less), a dynamic tool is needed to assess the operating characteristics as these major elements are added to a system. The tool then supports detailed evaluation of the tradeoffs. The tool is now ready for potential application in future research programs aimed at comprehensive and detailed comparisons of power electronics in fuel cell vehicles.

Fuel cell dynamic model for power electronics

A behavioral model of a fuel cell serves for the auxiliary power unit in the vehicle simulator. The fuel cell is connected to a nominal 300 V traction power dc bus in the vehicle via a dc-dc converter. The fuel cell receives a power command to be followed from a system-level controller. Given the commanded power, the fuel cell model follows the slow evolution of the actual available power as the cell tries to respond to the command. The model attempts to represent the dynamics between the fuel input and the electrical output. The actual electrical output power is calculated assuming that the dc-dc converter can adjust the current quickly to regulate the fuel cell voltage to a desired value.

The model was derived from simulated fuel cell data [4]. A block diagram of the model can be seen in Figure 1. A power command is delivered to the model. This command includes the power demanded from the driver, the commanded power to recharge the batteries plus all auxiliary power, as generated by the system-level controller. Given a typical operating output level of 0.6 V per cell, the necessary output current command and the required input fuel command can be calculated. Fig. 1 shows a first-order exponential time delay between the fuel input and the electrical output.

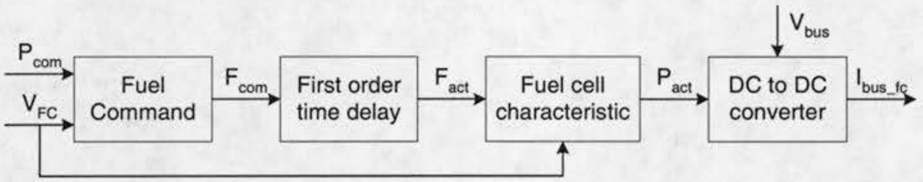


Fig. 1. Block diagram of fuel cell model.

The steady-state electrical characteristics of a typical single PEM fuel cell are shown in Fig. 2 for several fuel flow input levels. For any given fuel flow, and for a target voltage of 0.6 V/cell, there is a one-to-one mapping between output power and input fuel flow setting. Fig. 3 shows a single fuel cell's steady-state available output current at an operational voltage of 0.6 V across the possible fuel flow values. In the model, the cell represented in Fig. 2 is multiplied as appropriate to follow the right series and parallel behavior for a complete fuel cell stack.

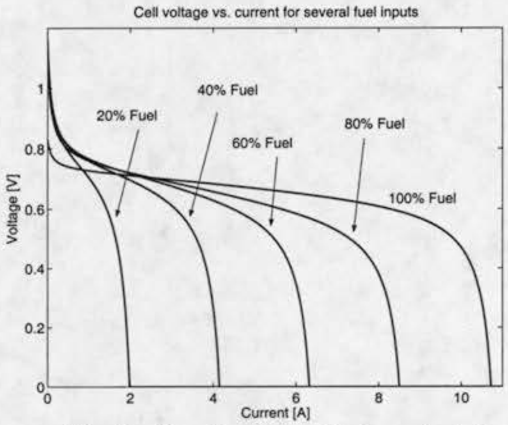


Fig. 2. Steady-state cell characteristics.

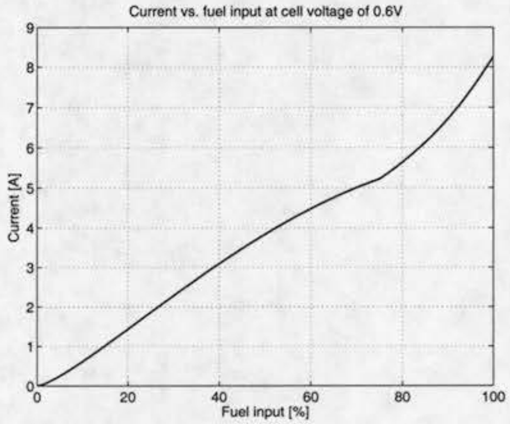


Fig. 3. Steady-state current vs. fuel input.

The second block in Fig. 1 is a first order time delay, which models the slow rate of change of the available output relative to the actual fuel input. Different time constants can be defined for fuel increase and fuel decrease. (Typically the system responds more quickly to a decrease). The dc-to-dc converter is modeled to enforce cell voltage of 0.6 V/cell by drawing the appropriate stack current, then delivers this current to the high-voltage traction bus.

Example system simulations

An initial simulation run has been performed based on 500 cells in series and a 20 s time constant. Relative to Fig. 2, about twelve stacks are combined in parallel. This results in nominal operating voltage of 300 V, and delivers up to about 50 kW to the traction bus.

A collection of sample simulation plots is given in Fig. 4. The figure shows behavior of the vehicle under the New European Drive Cycle (NEDC) [5], with a speed profile given in Fig. 4a. Fig. 4b shows battery state of charge as it evolves during the test. These batteries are larger than needed for this cycle, and show short-term changes of only a few percent. The dynamic electrical behavior is clear in Fig. 4c. The traction bus voltage drops significantly each time the vehicle accelerates and spikes during regeneration. The battery voltage is more damped because of connection inductance and capacitance between the batteries and the inverter bus. The fuel cell current behavior is shown in Fig. 4d. Here the 20 s time constant makes the fuel cell current lag the bus current, and the battery set must make up the difference. Fig. 4e shows the motor operating speed (there is a transmission in place, and gear shifts keep the motor speed in a reasonable range). Fig. 4f shows the dynamic motor torque requirements during this cycle. The negative peaks during regeneration are not shown.

Fig. 4g shows the power delivered to the vehicle axle over the drive cycle. Notice that this cycle for this vehicle involves rapid 60 kW peaks superimposed on a low average. Negative power flows during regeneration are not shown (for clarity) but are similar in magnitude. Fig. 4h shows the average battery output power as it impacts state of charge. The car is set up in this case for a modest recharge level to bring the battery SOC up. Fig. 4i shows commanded and actual fuel cell power. The time lag of the output is clear. This is influenced primarily by the simulation of fuel response, shown in Fig. 4j.

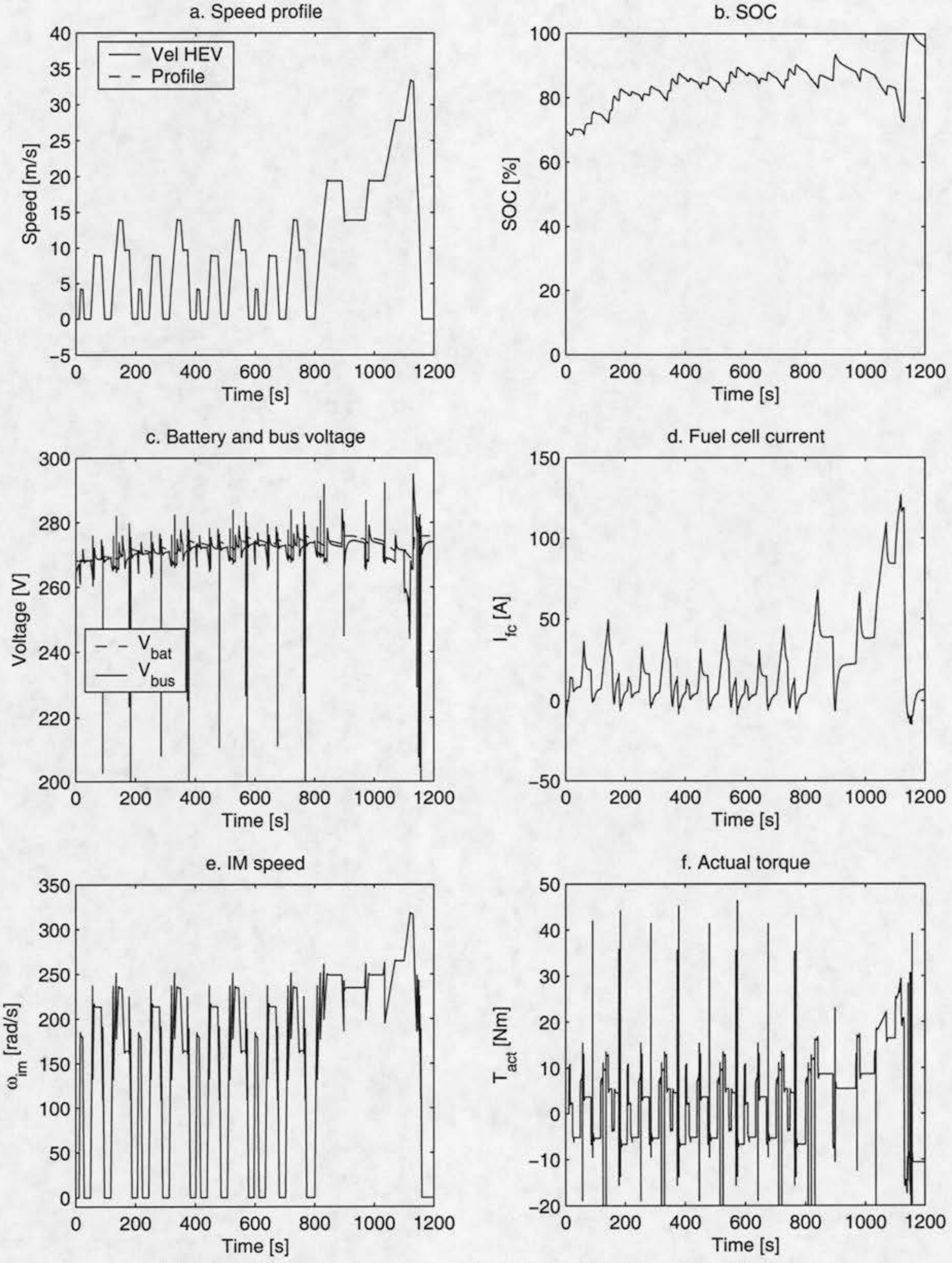


Fig. 4 a-f. Dynamic behavior of fuel cell vehicle during the NEDC.

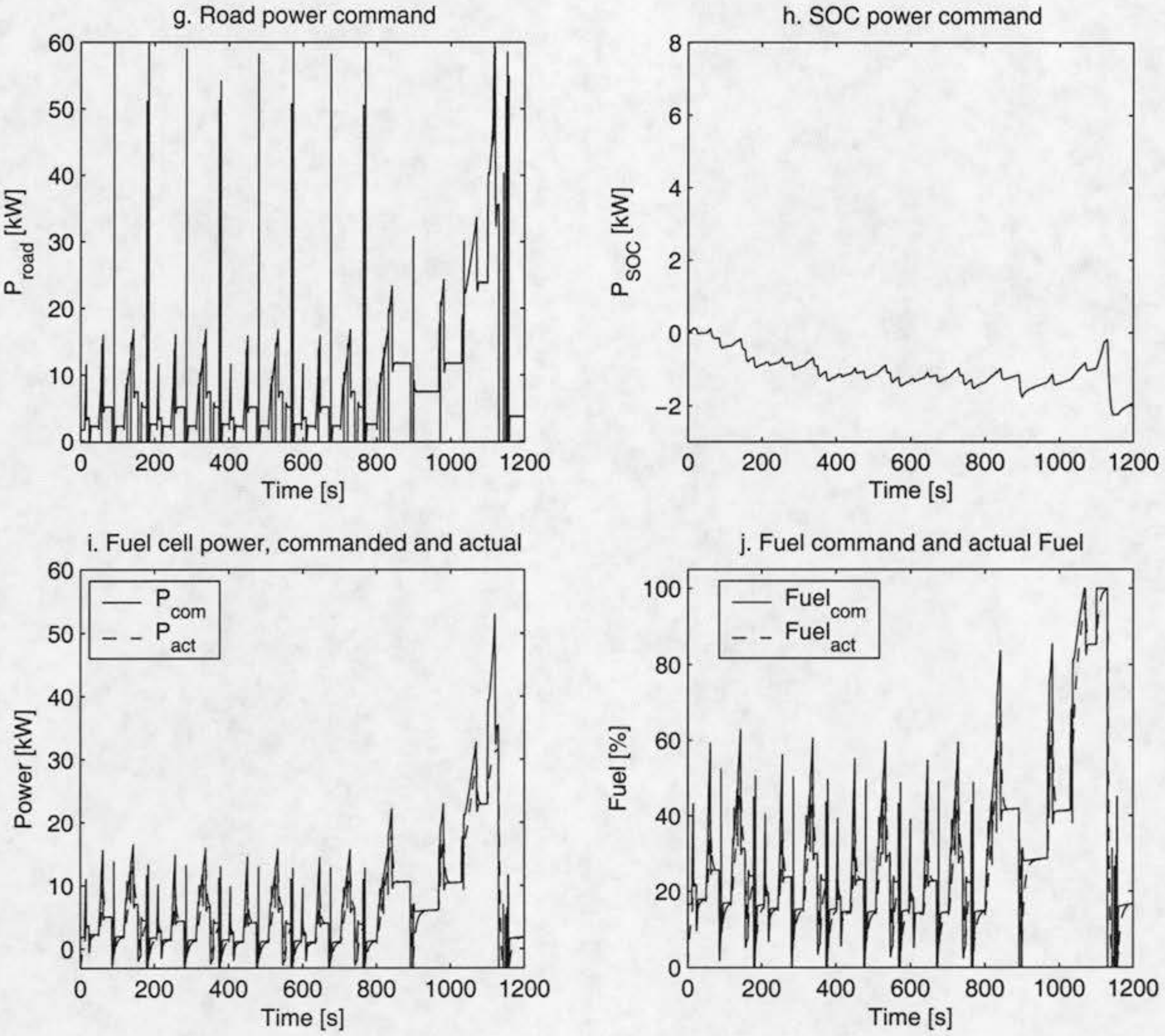
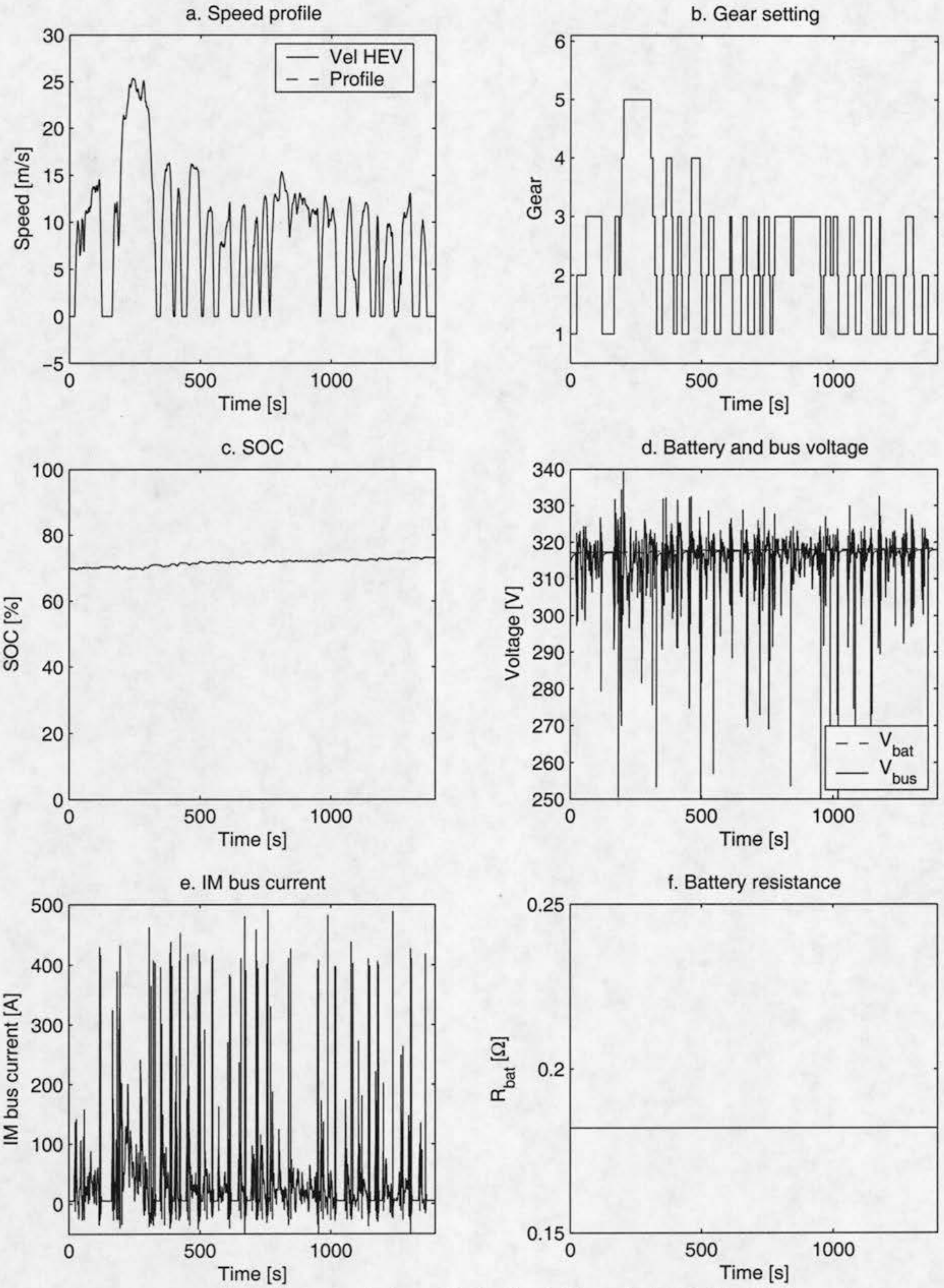


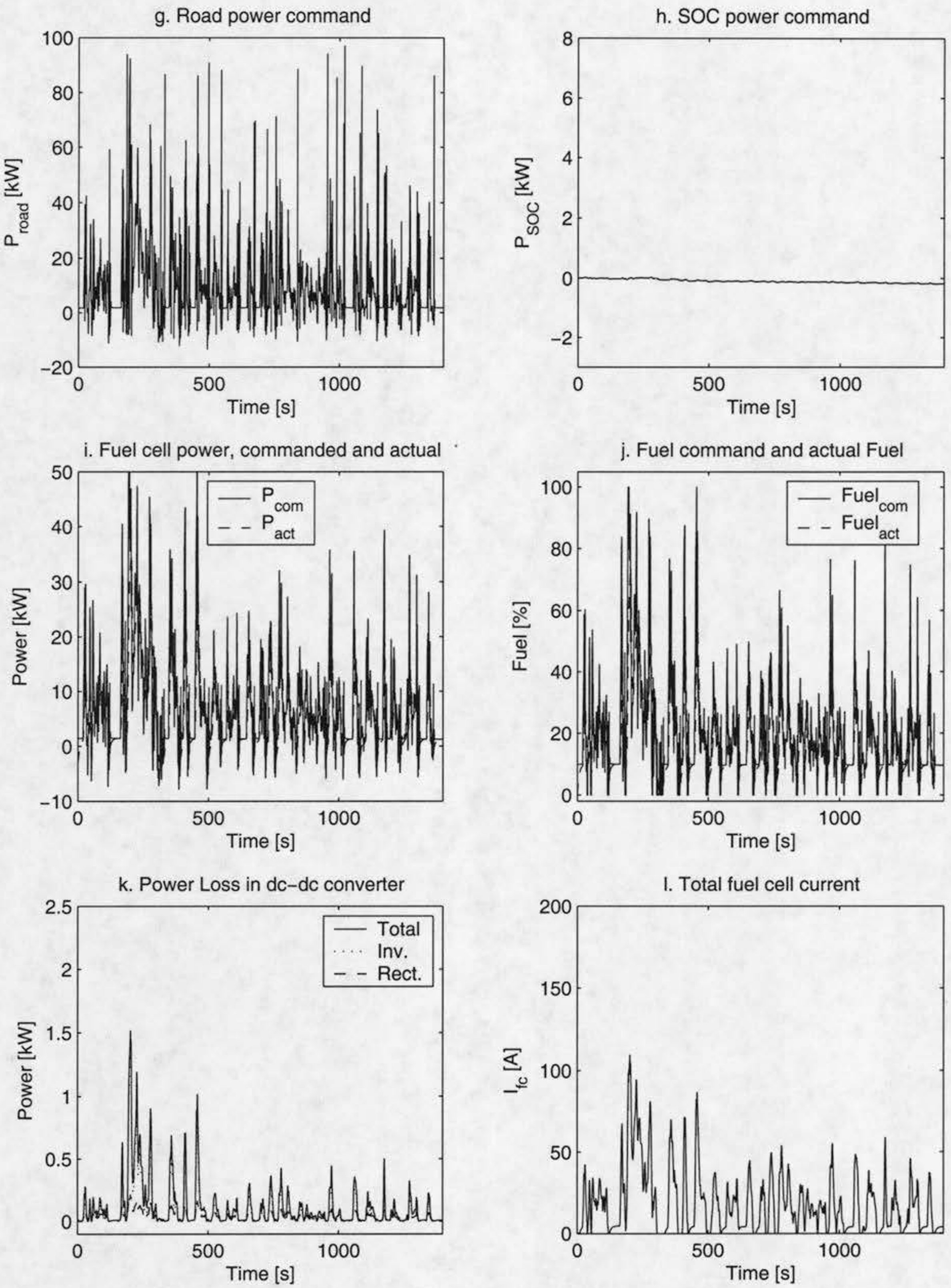
Fig. 4 g-j. Dynamic behavior of fuel cell vehicle during the NEDC.

The results in Fig. 4 show the importance of dynamic modeling for evaluation of power electronics requirements. Many of the ratings are determined by power or current peaks, since these can last several seconds during acceleration and braking. In some cases, the transients can be rapid enough to be absorbed in the thermal mass of electronic components, but this is not typical: the thermal issues relate to internal temperature of the semiconductor chips, which rise within seconds or even milliseconds during high power intervals. Even though the fuel cell operates with a slow time constant, its power still varies rapidly during a drive cycle in response to actual conditions.

Fig. 5 shows similar results for an EPA City Cycle. Fig. 5a shows the cycle profile. These results emphasize loss effects and other dynamic details. For example, Fig. 5j shows power loss in the



Figs. 5a-f. Dynamic simulation of fuel cell vehicle on the EPA City Cycle.



Figs. 5g-l. Dynamic simulation results under the EPA City Cycle.

fuel cell dc-dc converter during the drive cycle. Notice the highly variable nature of all simulated power traces, in this case even though the fuel cell is modeled with a 20 s first-order time delay. An important implication is that it is not accurate to estimate losses or efficiency based on nominal power values.

Models for ultracapacitor energy buffers

Ultracapacitors offer substantial advantages in hybrid electric vehicles. For instance, the power traces in Fig. 5 impose peak power levels in excess of 50 kW on the battery pack that must buffer fuel cell energy. For advanced batteries, this power level means that specific power rather than specific energy will be the governing factor that determines battery size and mass. Ultracapacitors achieve far higher specific power levels than batteries, and therefore provide a more effective means for handling high short-term power levels for acceleration and braking.

An ultracapacitor would not connect directly to the system dc bus, since its voltage must be adjusted over a wide range to make use of the stored energy. A bidirectional dc-dc converter is needed to make the bus connection and control energy flow. The converter adjusts the capacitor voltage and its rate of change to deliver or extract energy. In the most convenient arrangement, the maximum capacitor voltage matches the bus voltage, and a bidirectional boost-type dc-dc converter connects the capacitors to the bus. This configuration has the advantage of limiting the voltage stresses on the power electronics. It also supports simple control to provide wide energy storage range for the capacitors. The converter can be designed to respond quickly enough to cover any momentary energy shortfall from the fuel cell.

The proposed circuit configuration is shown in Fig. 6. The inductor interface allows the control to command ultracapacitor current, and track directly the energy injected or drawn from the unit.

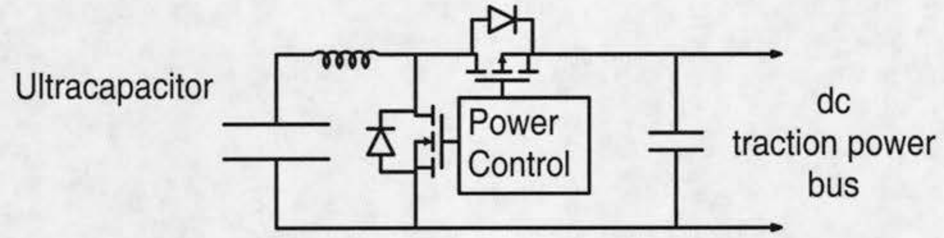


Fig. 6. Ultracapacitor and dc-dc converter interface.

Based on manufacturers' ratings, an ultracapacitor works best over about a 2:1 voltage range, which reflects a 4:1 energy storage range. This relatively limited voltage range has the advantage of keeping the dc-dc converter in a nearly linear operating regime. The dynamic model that has been prepared for the simulator uses an averaged converter model that takes into account switch conduction losses and augments them with a commutation loss calculation. The converter itself is expected to switch at frequencies on the order of 20 to 50 kHz. The input inductor assures that the current changes only by a limited amount during the 20-50 μs switching interval. This allows successful use of an averaged model. On this basis, the simulation can track losses as they vary with energy levels and rates in the ultracapacitor subsystem.

The ultracapacitor model itself (not shown) uses an ideal capacitance in series with an equivalent resistance. A low equivalent series resistance (ESR) is crucial for effective use of an ultracapacitor. Low ESR continues to be a focus of industry as the development of ultracapacitor technology continues. The boost converter's input inductor ensures that resonance effects within the ultracapacitor will not play a role in this application: the unit is treated as providing a desired (controlled) current.

Reference Vehicle Parameters

Table 1 lists vehicle parameters used for this analysis. They are assumed values for a large passenger sedan that uses relatively low mass structure and achieves a good drag coefficient. These are not intended to be "best case" values, but instead are broadly representative of fuel-cell-based hybrid vehicles. (As perspective, a 2005 model Chrysler minivan has frontal area of 2.90 m^2, drag coefficient of 0.35, and unloaded mass of about 1900 kg.)

Table 1. Vehicle parameters for reference comparisons.

Parameter	Value
Loaded mass	1800 kg
Drag coefficient	0.26
Frontal area exposed to air flow	2.8 m^2
Coefficient of rolling resistance	0.008 N/N

A MathCAD notebook developed for vehicle analysis was used with these parameters to compute required power levels and other performance attributes. This vehicle requires continuous traction power of 40 kW to operate at 65 mph on a 5% grade, and can maintain a speed of more than 95 mph on a level road at the same power. At this output power level, realistic efficiency values would be on the order of 93% for the motor and gear set and 97% for the motor drive inverter. This means that the electrical power available to the inverter should be 44 kW. If the fuel cell electric power conditioning process is 95% efficient, and adding 1 kW for vehicle "hotel loads" and control overhead, then the required fuel cell electrical output is $40/(0.93)/(0.97)/(0.95) + 1 = 47.7$ kW. Thus the fuel cell electrical output capability for a typical vehicle should be 48 kW to support continuous duty capabilities. This does not include fuel cell overhead needs such as pumps and compressors. For PEM systems, the overhead electrical load for these items and other system management components are often said to be about 15% of rated output power – pushing the electrical output requirement to about 55 kW.

Acceleration from 0 to 60 mph can be achieved in this vehicle in 12.0 s with peak traction power output of 92 kW. (This would also produce a short-term top speed of about 130 mph.) Since the fuel cell can deliver up to 40 kW of power to the axle continuously, the battery pack or capacitor pack must deliver the remaining 52 kW. With 93% motor and transmission efficiency and 97% inverter efficiency at peak level, this requires battery power of $52/(0.93)/(0.97) = 57.6$ kW. The sum of fuel cell electrical output and battery power requires the inverter to process input power of about 105 kW, although only for a brief interval. To permit the fuel cell to follow a transient with its 20 s time constant, the battery or capacitor could be asked to deliver even more than 58 kW, but the value will be limited to this level for the study here.

Notice that the power levels identified here are higher than the electric power levels in the Toyota Prius. This reflects in part the fact that the Prius has a partial "parallel" capability, in which mechanical energy transfers from the engine into the drive shaft without an electrical intermediary. At freeway speeds, this allows the use of a reduced-size traction system. Such capability is not possible in a fuel cell system. A fuel cell vehicle system is very similar to a pure *series hybrid* configuration, in which all energy is transferred in electrical form through the voltage bus. The traction system in a series hybrid system must handle 100% of continuous and peak power requirements.

The storage capacity needs can be estimated based on several assumptions. For example, given the 20 s time constant of the fuel cell output, the storage element should be able to deliver its full output for about 3 time constants, or 60 s. In present nickel metal hydride (NiMH) battery systems, the state of charge is kept in a narrow range to maintain balance and long life. If capacity drops 10% in 60 s at 58 kW load, then nominal battery capacity would need to be 35 MJ. This is almost 10 kW-hr – considerably more energy than is stored in the battery pack of a Prius. In practice, the battery would not need to carry full load during the entire 60 s interval. Through the use of 20% of the capacity rather than 10%, the size would capacity would drop to no more than 15 MJ, or 4.2 kW-hr. This is quite similar to the Prius pack size. For lead-acid batteries with 33 W-hr/kg density, this requires 126 kg. Peak power of 58 kW would require 460 W/kg power density – a plausible number for lead-acid technology. For nickel-metal hydride batteries, the specific power would need to exceed 500 W/kg by a substantial margin to allow battery pack mass reduction. Specific power tends to dominate battery selection in hybrid car applications. Other characteristics of nickel-metal-hydride batteries, such as cycling capability and good storage characteristics, have made them preferable to lead-acid batteries in hybrid cars.

An ultracapacitor has the important advantage that most of its energy capacity (typically 75%) can be used as it cycles. The extra usage means that only about 4 MJ, or 1.1 kW-hr, can meet the need. The specific power is very high (well above 1000 W/kg). However, this may not save system weight given the low specific energy of ultracapacitors. As specific energy and specific power of ultracapacitors continue to improve, they will become increasingly competitive with batteries in this application.

A summary of performance targets and results for this reference vehicle is provided in Table 2. The targets are not modest – they provide a vehicle well-suited to U.S. driving requirements.

Table 2. Power requirements and performance targets based on reference vehicle.

Attribute	*Value*
Speed that can be maintained on 5% grade	65 mph
Top speed (continuous, level ground)	95 mph
Acceleration ability, 0-60 mph	12.0 s
Continuous traction power (at axle)	40 kW
Fuel cell continuous electrical output rating	55 kW (44 kW plus conversion loss and overhead)
Peak traction power (at axle)	92 kW
Electrical bus power (at inverter bus)	44 kW continuous, 105 kW peak

Implications for Power Electronics Ratings

System-level requirements

The values in Table 2 define capacity targets for each of the major power electronic subsystems in a vehicle. The major subsystems include the traction inverter, the fuel cell power conditioner, and the energy storage interface. Other subsystems include a dc-dc converter for hotel loads and possibly a jump-start interface circuit. Table 3 lists the requirements and certain assumptions used here.

Table 3. Power electronics subsystems: ratings requirements and assumptions.

Subsystem	Rating need	Value	Assumption
Traction inverter	Continuous output	40 kW	97% efficiency
	Peak output	92 kW	97% efficiency
Fuel cell conditioner	Continuous output	55 kW	15% overhead power
	Minimum output	7.2 kW	Overhead power
Energy storage interface	Peak output or input	58 kW	To reach 92 kW
	Capacity	15 MJ or 4 MJ	Batteries or capacitors

Vehicle configurations

Consider three different vehicle configurations:

1. A series hybrid electric vehicle, with a complete full-power electric traction system. A small engine-generator *auxiliary power unit* supplies average cruising power.
2. A fuel-cell vehicle, in which the nominal fuel cell voltage is 48 V. Two distinct arrangements will be considered here. The first uses a 15 MJ battery pack, while the second uses a 4 MJ ultracapacitor set.
3. A fuel-cell vehicle, in which the nominal fuel cell voltage is 300 V. Again, two distinct arrangements involve a battery pack at 15 MJ or an ultracapacitor at 4 MJ.

Table 4 provides a summary of the major power electronics subsystems in each of the three major configurations and their sub-categories.

Notice that many of the major blocks are identical, and independent of the choice of energy source. One example is the electric traction system inverter. In all three configurations, the inverter manages 100% of motive power to the axle, so there are limited opportunities to adjust its ratings by altering the energy source. Another example is the 42 V/12 V electrical system, including operating auxiliaries such as electric power steering and brakes. Climate control is slightly more straightforward in

Table 4. Power electronics sub-systems in three vehicle types

Subsystem	Series hybrid	Fuel cell hybrid, 48 V	Fuel cell hybrid, 48 V, with ultracaps	Fuel cell hybrid, 300 V	Fuel cell hybrid, 300 V, with ultracaps
Traction inverter bus power	44 kW cont. 105 kW peak	44 kW cont. 105 kW peak	44 kW cont. 105 kW peak	44 kW cont. 105 kW peak	44 kW cont. 105 kW peak
Auxiliary power unit (APU)	Engine-generator plus controlled rectifier, 45 kWe output	Fuel cell plus dc-dc converter, 55 kWe output	Fuel cell plus dc-dc converter, 55 kWe output	Fuel cell plus bus control interface, 55 kWe output	Fuel cell plus bus control interface, 55 kWe output
Battery	300 V, 15 MJ, direct bus connection	300 V, 15 MJ, direct bus connection	No traction battery	300 V, 15 MJ, direct bus connection	No traction battery
Ultracapacitor	Not present	Not present	4 MJ, 90 F, variable voltage, with bidirectional dc-dc bus interface	Not present	4 MJ, 90 F, variable voltage, with bidirectional dc-dc bus interface
Hotel loads	42 V and 12 V dc systems	42 V and 12 V dc systems	42 V and 12 V dc systems	42 V and 12 V dc systems	42 V and 12 V dc systems

the series hybrid vehicle since the engine waste heat is available, but the fuel cell cars also produce low-grade waste heat suitable for passenger compartment comfort.

The primary difference between power electronics in fuel cell and series hybrid vehicle configurations is the auxiliary power unit (APU) interface. In a series hybrid car, the engine drives an electrical generator, usually an efficient ac machine. A controlled rectifier delivers power from the ac machine to the dc inverter bus. The rectifier circuit itself is relatively inexpensive, since silicon-controlled rectifiers (SCRs), the devices of choice, make excellent use of their semiconductor material. A drawback is that rectifier control can be complicated: the rectifier must act in a manner that tends to stabilize the engine, and must adjust quickly during fast transients. Rectifiers are relatively slow, so large filter components are helpful in this design. Rectifiers are very efficient, with levels as high as 98% in the power ranges of interest here. If the generator itself is about 94% efficient, the engine output required in the series hybrid configuration is 45 kW, or 65 HP. By way of comparison, the 2004 Toyota Prius engine is rated at 70 HP.

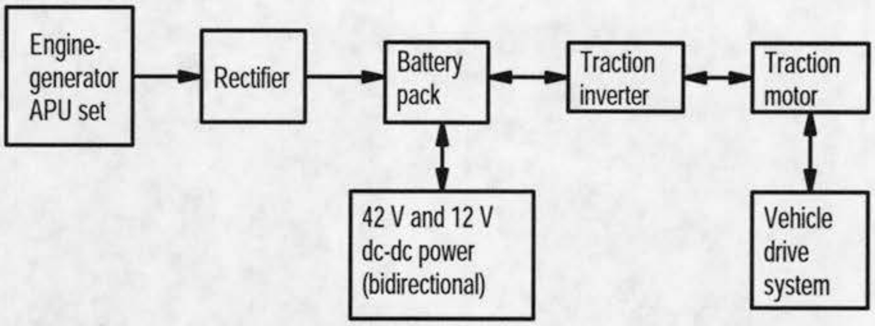


Fig. 7. Block diagram of series hybrid electric vehicle configuration.

Fig. 7 shows the block diagram of the series hybrid configuration. In this arrangement, the battery pack defines the dc electrical bus. The rectifier is assumed to be unidirectional. Ideally in a series hybrid, the engine and generator are tightly integrated and provide a reversible starter-alternator function. Reversible function is difficult in a rectifier-based system, so some alternative drive power electronics would be required. One approach is to treat the generator interface as a "reverse inverter," with the ac connection to the machine and the dc connection to the system bus. This makes the energy interface power electronics similar to the traction power electronics and is a complicated solution.

In fuel-cell hybrids, the APU power electronics interface is relatively straightforward – a dc-dc converter with good control capability. This arrangement offers control advantages relative to a rectifier. As in the series hybrid, a typical arrangement involves unidirectional energy flow. However, fuel cell operation and start-up could benefit from bidirectional flow (just as in a combined starter-alternator). Bidirectional capability is much easier to add to a dc-dc converter than to a rectifier. From a purely power electronics perspective, a fuel cell is easier to address than an engine-generator set.

The most important distinction between the battery and ultracapacitor arrangements is that a battery configuration connects directly to the main dc bus. The batteries serve as the voltage regulator for this bus, and the overall system operates at near-constant bus voltage. With ultracapacitors, a bidirectional dc-dc converter connects the capacitors to the bus and controls capacitor current. In a case in which no bus batteries are present, the ultracapacitor converter would require fast response, and would adjust the current as needed to regulate the voltage. Thus the main difference between configurations with and without ultracapacitors is that the former require a fast bidirectional dc-dc converter. If an ultracapacitor is used to augment a small battery pack rather than replace the pack outright, then the ultracapacitor and its converter become a self-contained energy storage unit with more modest dynamic requirements.

The distinctions between 48 V fuel cell and 300 V fuel cell designs are more extensive. Since 48 V is too low for useful traction power, a dc-dc step-up converter is required to interface the fuel cell to the main electrical bus. This dc-dc converter would be controlled to draw a pre-determined current from the fuel cell. Most likely the current would be adjusted dynamically to match the fuel cell output capability under a given set of operating conditions. The 48 V system, although conventional, generates significant extra cost because of the extreme currents (up to 1200 A) on the low-voltage side.

Fig. 8 shows a block diagram for the 48 V fuel cell system. The block diagram shows a possible advantage of the arrangement: the 48 V fuel cell stack could provide an alternative direct feed to the vehicle 42 V/12 V system, which would skip some losses in this conversion step. The diagram shows both a battery set and the ultracapacitor. This is a logical arrangement if the battery pack is used to maintain bus regulation – a challenge with a 48 V fuel cell. It is possible that the batteries could be avoided and a "virtual bus" could be used. In this case, fast response from the ultracapacitor interface would be required to regulate the bus voltage.

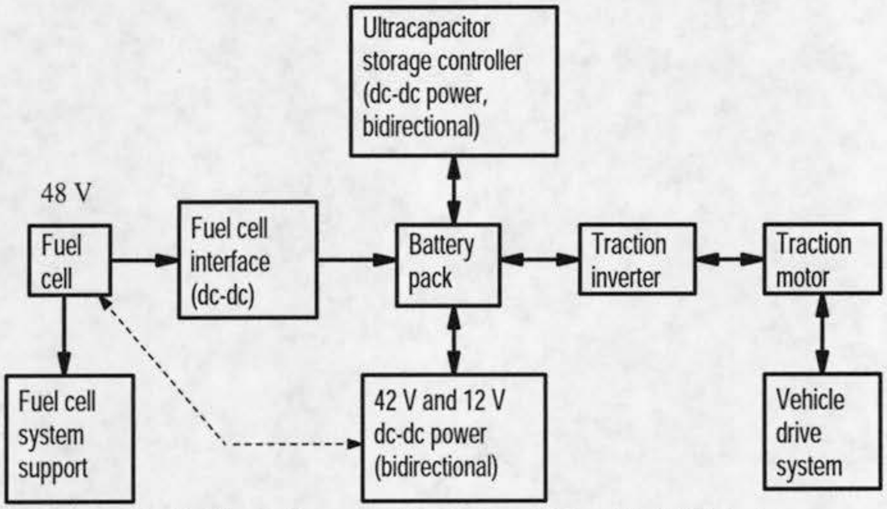


Fig. 8. Block diagram of fuel cell vehicle with 48 V stack.

With a 300 V fuel cell stack, other alternatives emerge. One choice is to retain a dc-dc interface structure similar to Fig. 8. This allows the fuel cell current to be controlled dynamically. The converter cost would be substantially lower than for the 48 V system since currents are much lower and the voltage conversion ratio would be close to one. Another choice connects the fuel cell passively to the dc bus. Only filter elements are used in this case, as suggested in Fig. 9. Bus voltage control relies on the ultracapacitor interface in this case, although to a lesser degree than it would for a 48 V fuel cell.

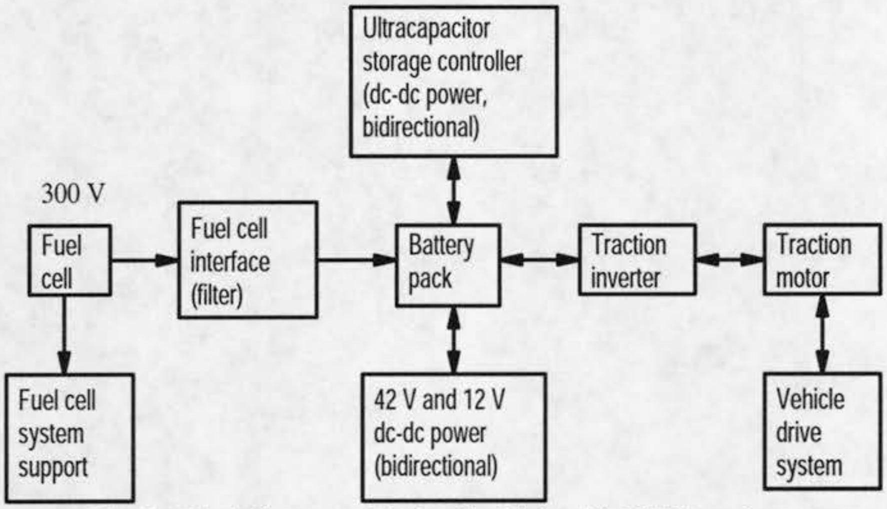


Fig. 9. Block diagram of fuel cell vehicle with 300 V stack.

From a power electronics perspective, the three major configurations are relatively easy to compare. The simplest is the one with a 300 V fuel cell stack and battery set as in Fig. 9 but without the ultracapacitor interface. The fuel cell controller would adjust fuel supply to keep the voltage close to 0.6 V/cell at all times. The difficulty is that fast bus voltage swings, as occur during acceleration or braking, may result in uncontrolled fuel cell current. From a control perspective, the ultracapacitor adds substantial capability at extra cost.

Cost considerations

Consider first the vehicle configuration with a 48 V fuel cell. Let us explore the implications for the fuel cell power conditioning electronics in more depth. To best support fuel cell energy control, a current-controlled converter interface provides fundamental advantages [6]. The 48 V level leads to nominal current of 1200 A. At these high power and extreme current levels, the overall electrical system would have excessive mass if designed entirely at 48 V. Consequently, the system configuration is unambiguous: a full-bridge current-sourced forward converter would be used to step up the 48 V fuel cell output to a drive system bus voltage level – taken as nominally 300 V for this work.

Since fuel cell voltage is not well regulated, a 48 V nominal output is assumed to correspond to 0.6 V/cell, and implies a series stack of 80 cells. The open-circuit voltage could exceed 80 V, although this would not be a normal operation occurrence since the fuel cell requires a substantial overhead load. However, the result is that 60 V semiconductors would not be suitable, and it is most likely that 100 V parts would be required. The combination of ratings, 100 V and 1200 A, can be met with parallel combinations of power MOSFETs. Here is a summary on this basis:

- Rating requirements for bridge: 100 V, 1200 A input side devices.
- Best devices in class at present: 100 V, 50 A TO-220 units with 0.03 Ω resistance (example: On Semi NTP52N10).
- Need: 24 devices in parallel for each switch in the bridge. Total count: 96 devices (ignores redundancy requirements in part because the 50% duty provides a bit of current overhead).
- This yields 1.5 V drop (3 V in bridge) and has at least 6% on-state loss at rated load. Estimated total loss: 10%.
- If a negotiated cost of $0.30 per part could be reached, the semiconductor cost is $28.80. Given the 55 kW rating, this is a very low $0.52 per kW. Passive parts, packaging, and cooling could raise the conditioner costs by at least an order of magnitude.

Now consider a 300 V fuel cell rating. Device ratings are on the order of 200 A in this case. The most likely devices would be insulated-gate bipolar transistors (IGBTs), which have a forward drop on the order of 2 V. The bridge circuit places two in series, which yields a total drop of 4 V and on-state loss of only 1.3%. Total loss of about 2% is plausible. IGBTs have limited voltage range selection. For a 300 V bus the closest rating value is 600 V. Although higher voltage ratings are available, it is likely that safety and cost considerations will keep the bus level in hybrid cars close to 300 V. The 200 A rating is more difficult. IGBTs of a given rating are somewhat cheaper than their MOSFET counterparts because they require less silicon. The drawback is that IGBTs cannot be connected in parallel as easily as MOSFETs. Consequently it seems most likely that full multi-chip IGBT modules will be needed. The packages for these devices are relatively expensive. Here is a summary of requirements:

- Rating requirements for bridge: 600 V, 200 A input side devices.
- Best devices in class at present: 600 V, 200 A module half-bridge units with 2 V forward drop.
- Total count: 2 device packages.
- This yields 4 V drop in bridge and about 2% total loss at rated load.
- If a negotiated cost of $40 per part could be reached, the semiconductor cost is $80. Given the 55 kW rating, this is still modest at $1.45 per kW. Passive parts, packaging, and cooling would be simplified in this arrangement since multiple semiconductor interconnections are avoided, so the end cost is likely to be somewhat lower than for MOSFETs in the 48 V system.

The most difficult question remains that of the fuel cell voltage selection. A 300 V cell most likely leads to much more efficient power electronics, probably at lower cost, than a 48 V system. However, an operating voltage of 300 V implies 500 cells in series – a daunting fabrication prospect. The 48 V cell stack avoids some of the difficulty with long series strings, but has very high currents and requires large busbar arrangements to deliver the current without excessive loss.

System comparison comments

All three vehicle configurations use the same traction system. If batteries are present, the bus control is also identical. From an operational perspective, the 300 V fuel cell system offers major advantages. The fuel cell converter for 300 V should provide efficiency close to 98%. If control issues can be addressed effectively, it should even be possible to avoid this converter and use a passive filter as in Fig. 9. In the 48 V fuel cell system, the converter efficiency is more likely to be about 90%. The difference between 90% and 98% efficiency, a factor of five in terms of losses, is particularly problematic in this part of the system. Not only does it increase the fuel cell power requirement, but it also generates a large thermal management challenge in a nonideal location.

The ultracapacitor interface is a useful addition, but introduces severe power electronics requirements. Based on the reference vehicle, the necessary converter must deliver 58 kW peak and is bidirectional. Since the peak could last for nearly 60 s, the effect on the power electronics is that the 58 kW rating is essentially continuous. This makes the ultracapacitor dc-dc interface similar in rating and size to the traction drive. The control is simpler than for the drive, and a set of four devices can be used rather than the six used in the drive, but the cost is likely to be on the order of 60% of that of the traction inverter. Ultracapacitor energy storage is not a low-cost alternative.

State of the Art Related to Power Electronics Advances in Hybrid Vehicles

Solid-state devices

Power electronics in the ranges of interest has been progressing primarily because of advances in device ratings. The most recent power MOSFETs support high current levels (hundreds of amps) at bus voltages in the 12 V nominal range. Parts suitable for power levels up to about 10 kW in the 48 V nominal range are available. The most important developments involve the IGBT. These devices are available in standard 600 V, 1200 V, and 1700 V ratings. Individual packages (typically with multiple dies) are available at current levels up to about 600 A. The devices continue to improve.

For MOSFETs, the primary industry drivers are PC markets and microprocessors at system voltages of about 12 V and below, and telecommunications markets at 48 V. The corresponding device voltages are 20 V to 30 V at the low end, and 75 V to 100 V at the high end. While there is considerable work in progress related to 42 V automotive hardware, automotive markets are small relative to the others and are not dominant technology drivers.

For IGBTs, the primary industry drivers are electronic motor drives, although there is also relevant activity because of electronic ballasts for compact fluorescent lighting. As device voltages increase, there is also a promise of electric utility applications at the distribution level. The technology drivers at 120 V and 240 V ac levels are almost entirely motor drives, suitable for device voltage ratings of 600 V. Today, 1200 V devices have advantages. They are used in motor drives designed for 480 V ac to about 600 V ac – levels that dominate industrial drives applications. There is active work to push voltages even higher. Eventually the devices will support 2300 V ac drives directly, and will extend

IGBTs to motor drives in excess of 1000 kW. Again, automotive markets for IGBTs are not dominant. It will be important to leverage industrial drive applications to gain benefit for automotive systems.

For both device classes, the biggest challenge today is to create cost effective packages with excellent thermal characteristics. IGBT packages are very expensive and often have vibration sensitivity. New developments in high-current MOSFET packages may have some impact on IGBT applications. This is discussed further below in the Research Needs section.

The distinct voltage levels for existing devices (up to 100 V for low-loss MOSFETs and either 600 V or 1200 V for IGBTs) imply fixed dc bus voltages for their respective applications. For MOSFETs, 48 V represents a good level with a strong industrial base. For IGBTs, a bus voltage of 300 V nominal (with an actual range of about 280 V to 400 V) is a good match to 600 V devices. While other voltage levels are physically possible, few others have the industrial application base that 48 V and 300 V enjoy. For example, MOSFETs are available that could support a 200 V dc bus. Their applications tend to be confined to relatively low power levels, and the industrial base in this range is limited. Although the industry is moving to 1200 V IGBTs, the implied bus voltage (600 V dc) seems high for passenger cars. A fuel cell stack voltage of about 300 V dc interfaces well to IGBT systems, and indeed the main traction drive is a near-trivial adaptation of off-the-shelf drive technology. A fuel cell stack at significantly lower voltage will require a powerful dc-dc converter with extreme low-side currents.

Impact of new semiconductor materials

There is active research today on power semiconductor devices based on SiC, GaN, and even diamond. These materials have some merit with respect to automotive. Most significantly, they can operate at junction temperatures approaching 400° C, which would permit direct interfacing to the high-temperature engine cooling loop in a hybrid car or perhaps even a cooling loop for an SOFC fuel cell stack. The drawback is that these materials are in early development, and no present packages support full use of their capabilities. They also carry higher inherent costs than conventional Si devices.

The theoretical advantages of all three materials have been well articulated in the literature and will not be addressed here. The issue in the context of electric and hybrid vehicles is whether they can make substantial inroads into broad power electronics applications. It seems likely that compound materials will have impact only following their broad application to motor drives and similar mass markets. The conventional wisdom is that SiC is likely to play the most important role, since its development seems more advanced and small power devices are on the market. On the other hand, GaN has the advantage that it supports heterojunction device design in the AlGaN material system. AlN has exceptional thermal properties. Diamond, like the others, is being pursued for its high voltage capability, a less important factor in automotive applications.

Other materials

Fuel cell power systems require intensive use of magnetic materials. Inductors for filtering and for transformers are crucial elements. One intriguing material in this context is powdered iron. In powdered iron magnetic devices, finely ground iron is formed with a ceramic or other non-magnetic composite to create a low-permeability material in nearly arbitrary shape. The material is sometimes termed *soft magnetic composite* (SMC). It is very low in cost, but is somewhat lossy in power electronics applications. A similar material based on ground ferrite, with the trade name "Coolmu" is popular in advanced power supply designs. If losses can be reduced and permeability raised in powdered iron materials without a cost penalty, these materials would have strong promise for fuel cell vehicle applications. They would make it feasible to use magnetic devices throughout a conversion system at modest cost per unit power.

Capacitors remain an important component and challenge for multi-kilowatt power conversion. At these power levels, electrolytic capacitors are unavoidable. However, they typically limit the life and reliability of a conversion system. Recent developments that use polymer electrolytes are of interest. Capacitors based on these materials have dramatically reduced losses and are likely to have better reliability characteristics. The drawback today is high cost. Ceramic and film capacitors are preferred when feasible, but have extremely high cost and low energy storage density.

Electric machines

Electric machines are mature enough to meet the specified FreedomCAR traction needs in essentially their present form, given the right operational combination. Based on motor re-rating work [7], for example, it is possible to identify a commercial off-the-shelf motor that could be re-rated for traction duty to achieve 30 kW continuous and 55 kW peak power, with a single-unit retail list price under $200 and motor mass under 30 kg. This machine meets the requirements with air cooling, thus avoiding the extra expense of a liquid cooling loop. It is reasonable to infer a manufacturing cost below $100 for such a unit. Permanent magnet (PM) materials (notably NdFeB) can be used to further reduce mass in this application. However, the relatively high cost of PM materials makes it unlikely that 30 kW continuous power and 55 kW peak can be achieved with a manufacturing cost under $100 with PM machines.

An important consideration with respect to electric motors in this power range is that production is mature and quantities are already high. Automotive applications represent a tiny fraction of the market compared to industrial applications and even home appliances. Automotive quantities, however, are probably substantial enough that custom packaging could be provided and the re-rating process supported without additional cost. It is possible that a simple package could be designed that would support liquid stator cooling at no extra cost.

Interior permanent magnet (IPM) machines are generating considerable interest today, and have proven potential in electric traction. For perspective, it is important to recognize that the induction machine designed for the General Motors EV1 in the early 1990s is more powerful and robust than present IPM designs. It achieves a much higher specific power at lower cost. Traditional machines such as induction machines have significant advantages in traction applications and should not be discounted.

One crucial issue that has not been addressed effectively is that of the motor/mechanical interface. Any reasonable traction motor requires a gear ratio (and couplings) between the motor shaft and drive shaft. It is conventional wisdom that a single gear ratio is desired, but this is inconsistent with electric motor ratings and capabilities. In fact, a gearbox with a few selectable ratios yields much better design tradeoffs. Given the advanced control capability of a traction motor, simple gearbox designs that use active synchronization are feasible in an electric drive system.

There is an opportunity for sponsored research to develop innovative, simple, low-cost transmission systems that make good use of motor control capability to support multiple gear ratios. Such a system could be shifted with solenoids or other electromechanical actuators to avoid the need for the driver to control the transmission. In past work, motor control has been used to provide clutchless manual transmission capability [8]. This issue is discussed below in more detail.

There are many other electric motor applications in vehicles, ranging from seat adjusters and window lifts to power steering and suspension actuators. A key opportunity here is to standardize the operating bus voltage (most likely based on the emerging 42 V system), then develop low-cost inverters across a full range of power levels to meet requirements. In these applications, MOSFET inverters are expected to dominate. Small motors exist in high volume in cars, so in this arena there is enough market leverage to have major impact.

Research Needs

Based on the three vehicle configurations and also on more general design considerations for hybrid vehicles, a number of important research needs can be identified. Significant issues include:

- Low-cost semiconductor packages for IGBTs.
- Soft magnetic composite materials with improved permeability and reduced loss.
- Extension of polymer electrolyte capacitors to full dc bus ranges.
- Tradeoffs for fuel cell voltage.
- Controls and circuits that support reduced converter complexity.
- Better methods for bidirectional conversion.
- Low-cost gearboxes that use motor control for synchronized shifting.

- Fundamental understanding of dynamic capabilities and dynamic energy tradeoffs in fuel cells.
- Package and device integration.
- Controls that support "soft-bus" designs.
- Dynamic system simulation that identifies specific losses and short-term energy tradeoffs.

Each of these is discussed and summarized in turn in the sections below.

Low-cost semiconductor packages for IGBTs

Expensive semiconductor packages with limited heat transfer capability are a critical limitation in traction drives. Package cost and performance improvements need high priority to meet FreedomCar objectives.

Traction inverter drives for hybrid electric vehicles, as well as other power electronics subsystems including dc-dc converters and active rectifiers, use IGBTs as their primary operating switches. These devices are most likely to be used in 600 V ratings, although 1200 V devices are also plausible. Lower power modules, such as electric power steering or 42 V automotive system elements, are likely to use power MOSFETs instead.

A major system design issue today for IGBTs is the package. Typical packages are large, complicated, and implemented with wire bond techniques that do not hold up well under vibration. The individual parts are very expensive (up to $100), but in most cases the package dominates the cost. There is an urgent need for low-cost high-performance packages. Package improvements will reduce system costs substantially. The elimination of wire bonds and package innovations that yield better thermal performance will have substantial impact on system reliability.

The most innovative work along these lines is the DirectFET™ package from International Rectifier [9]. In this package, a power MOSFET die is connected directly to a circuit board, with a copper clip on the top of the chip to permit drain connection. The package exceeds traditional performance limits in almost every aspect, including cost. It facilitates cooling and improves dynamic electrical characteristics. There is a significant opportunity for government labs to encourage more of this industry innovation. Government labs can help identify markets and facilitate interactions, while power semiconductor manufacturers must do the actual development work of IGBT packaging. There are fundamental reasons to expect that this packaging technique can be extended to IGBTs and applied in electric and hybrid vehicle applications. It would be expected that such development could occur over an interval of less than a year, and that costs could be recovered in increased sales and margins to drive manufacturers as well as to automotive users. The commercial risk is relatively low, so industry could play the primary role.

Package improvements are essential not only to FreedomCar but to the future of fuel cell power processing. Low-cost IGBTs in the 100 A and above range would have rapid impact on a host of power processing applications.

In summary, there are significant research needs in low-cost semiconductor packages for IGBTs:

- This is a very important need, and perhaps dominates possibilities for cost reduction.
- Dramatic advances in MOSFET packages have taken place.
- Can national laboratories encourage manufacturers to extend low-cost package innovations to IGBTs?
- In this case, the players in general are in industry. Government can help bring together major users (motor drives, semiconductor suppliers, package experts) to encourage this innovation and establish market size. Government can also help establish standards.
- A 600 V, 200 A IGBT with packaged price under $10 would be a major breakthrough.
- This should be mainly a question of market pull, and should be a relatively short-term effort.
- Players include International Rectifier, IXYS, Fuji, Powerex, other power semiconductor makers.

SMC materials with improved permeability and reduced loss

Powdered iron in a ceramic or resin matrix is sometimes termed *soft magnetic composite* (SMC) material. SMC materials are low in cost and can be molded into convenient shapes. Even very large cores can be fabricated at low cost. The cost and shape advantages are significant.

Because the magnetic material is held within a non-magnetic carrier, the relative permeability of these materials is low. They are often termed *distributed air gap* materials because of the non-magnetic content. In power electronics applications, a range of permeabilities is needed to trade off physical size and inductor energy storage. The permeability of typical SMC materials is lower than the ideal in many cases. A relative permeability up to 75 is available. This modest value is suitable for inductors with low values but hard to use for inductors with high values or for transformer cores. A more significant drawback in power electronics applications is the relatively high loss density of these materials. They are usually acceptable in drives applications, in which switching frequencies rarely exceed 25 kHz, but are marginal in dc-dc converter applications switching above 100 kHz.

In the past few years, there have been modest advances in SMC materials. Some manufacturers use ground permalloy powders or other more advanced alloys. A few use ferrite powders to gain extremely low losses, at the expense of low operating flux density. Improvement of SMC materials is an excellent opportunity for research scientists at national laboratories. There is only limited fundamental work in industry at present. Can nanoformed iron powders, for example, support a much wider range of permeabilities with low cost and acceptable loss? Are there other low-cost alloys that can be used for SMC? Can relative permeabilities be adjusted to desirable values in the range of 150 to 500 or even more? If relative permeability of SMC materials could be improved by about a factor of four and losses decreased by a similar factor without significant cost impact, these materials would make power converter designs much easier to implement in the ranges of interest.

A reasonable project could probably be performed in a two-year time frame with a budget to support two or three magnetic materials experts. Such a project would have as its objectives substantial improvements of SMC materials. As additional incentive, there are new electrical machinery designs based on exotic pole shapes that can be implemented with SMC materials [10]. The present generation of materials is inadequate for this task, but substantial improvements could bring about new opportunities in motor design. Since nanofabrication is likely to be a factor, the necessary research and development is probably better suited to national laboratories than to industry, even though the commercial risk is moderate and successful advances would be strong factors in the marketplace.

The fuel cell systems for these vehicles (such as 48 V fuel cells at 55 kW) require inductors rated at more than 1200 A. SMC materials have promise for cost-effective large inductors that could help make fuel cell implementation practical.

Extension of polymer electrolyte capacitors to full dc bus ranges

Electrolytic capacitors are necessary filter elements in drives up to about 500 V. Their failure modes are troublesome (most types fail as short circuits), and they represent a reliability-limiting element in many power electronic systems. Polymerized organic semiconductor, or *Oscon* capacitor electrolytes have appeared in the past few years. These materials are now being used in the manufacture of low-voltage capacitors.

Oscon capacitors have much lower loss densities (lower by factors of ten or more) than conventional manganese dioxide aluminum electrolytic capacitors. They also have different failure modes and promise better reliability. Unfortunately, they have been implemented only in low-voltage applications up to 35 V. In contrast, 42 V automotive applications require capacitor ratings of 63 V or more, while hybrid vehicles require 400 V and above.

It is interesting to notice that Toyota has been reconfiguring systems to avoid large electrolytic capacitors. One reason for the 500 V traction bus voltage in the 2004 Prius appears to be that highly reliable film capacitors can be used in place of electrolytic capacitors at this voltage level. The drawback is that film capacitors are large and relatively expensive. If Oscon capacitors can be extended to the 400 V level, many difficult system design challenges can be mitigated.

The development of high voltage Oscon capacitors could benefit from interaction between government laboratories and industry. Given that the objective is to extend the state of the art of a new material technology by an order of magnitude, this probably represents a high risk, high potential return activity. The materials issues and other challenges could be a good match to national laboratory expertise.

Successful extension of Oscon technology would at least double the reliability of most power electronic systems.

Tradeoffs for fuel cell voltage

The selection of operating voltage is a critical tradeoff in any fuel-cell-based system. In general, power electronics improves at higher voltages while fuel cell implementation benefits from lower voltages. In the context of FreedomCar, a fuel cell operating output of at least 300 V would avoid an entire dc-dc conversion stage, and would maintain reasonable current values throughout the high-power traction subsystem. The elimination of a dc-dc stage in particular is important for maximum system efficiency.

The problem is that a 300 V fuel cell stack requires about 500 cells in series. Each must be electrically isolated. In an aqueous system such as a PEM fuel cell, such extremes seem likely to make fuel and waste management difficult, not to mention seals and overall stack construction. The opposite extreme is a single cell, in which case we wish to produce 55 kW at nominal voltage of 0.6 V. for a current of more than 90000 A. It is not feasible to process extreme currents efficiently at low voltages with reasonable power electronics.

The combination of challenges implies that some intermediate fuel cell voltage might be needed to optimize the design of a practical hybrid vehicle. This report has already proposed that 48 V might be suitable as an appropriate intermediate value. This is justified by specifications of existing fuel cell systems. However, higher voltages always benefits the power electronics design. It is not clear whether basic research has been conducted both to elucidate the engineering implications of any given voltage level or to show how the voltage choice affects system performance. The tradeoffs do not represent a continuum. At 48 V, for example, protection issues, hardware requirements, and other practical implementation aspects can leverage existing products for telecommunications power and for emerging 42 V automotive systems. At higher voltages, there is relatively little merit until about 300 V dc is reached. At that point, hardware used in motor drives and industrial equipment comes into play.

The selection of fuel cell voltage appears to be an appropriate joint research activity across industry, government laboratories and university teams. A team of two graduate students who span power electronics and fuel cells could provide a detailed evaluation of tradeoffs. The voltage choice also affects the choice of conversion topology, and this could be addressed within the same project. Industry collaborators would be important to bring out key engineering issues associated with series fuel cell stacks. It is reasonable to expect that a twelve to fifteen month project to fund two students and a faculty advisor would lead to a much better understanding of these issues. Partners could then begin to discuss standardization.

Controls and circuits that support reduced converter complexity

Converter complexity can be reduced to an extent by combining functions or by using a high-frequency ac bus structure in place of a dc bus. In the fuel cell arena, reduced complexity can take the form of an ac link method introduced in Japan in 1990 [11, 12]. Recently, this approach has been simplified through the use of alternative forms of pulse width modulation [6]. These methods, while promising, require basic pre-competitive research and development for complete implementation.

Issues of control and converter complexity reduction are appropriate topics for a university environment, in partnership with national laboratories as power levels increase. A university-run project, for example, seems likely to lead to scaled versions of converters, perhaps in the 1 kW to 10 kW level. To scale up to the full 55 kW level needed for FreedomCar, the equipment and expertise available in national labs and in industry would be of considerable benefit. Related areas of investigation include the application of coupled or integrated magnetics to the design of power converters at levels up to 55 kW. Such a project represents a long-term effort that could lead to significant cost-performance improvement as hybrid vehicles are further developed. It is likely to be fruitful on a five-year time scale, funded at a moderate level (two students and one faculty member) at two or more universities over the period.

Better methods for bidirectional conversion

Key power electronics interfaces, especially those for batteries and ultracapacitors, require energy flow in both directions. For inverters, such as the traction drive inverter, bidirectional conversion is inherent and no extra engineering is required. Most dc-dc converters, in contrast, are inherently unidirectional. Bidirectional conversion in dc-dc converters brings about additional failure mechanisms, increased control complexity, and more expensive circuit configurations. There is a continuing need for basic research in bidirectional dc-dc conversion, especially at power levels above 1 kW. At present, this is considered to be a relatively specialized area, and few researchers are pursuing it. However, bidirectional conversion has important implications for future energy systems, especially related to distributed generation.

This topic is suitable for university-level basic research. What are good ways to scale up bidirectional conversion in dc-dc systems? Are there simplified circuits that support both directions with minimum added complexity? Can additional failure modes be characterized and avoided? These and other questions should be appropriate for university research work over a three to five year interval. The appropriate resource level is probably a set of two or three schools funded to support two students and a faculty member over a three-year interval. This should be sufficient time to firmly establish the issues and advantages that can be achieved.

Low-cost gearboxes that use motor control for synchronized shifting

Electric machines in size ranges above 1 kW produce a torque that is proportional to the product of internal magnetic flux density $\mathbf{B}$ and winding current density $\mathbf{J}$. In practical devices made of steel and copper, the flux density is limited by magnetic saturation and the current density is limited based on thermal considerations. The implication of limits on $\mathbf{J}\times\mathbf{B}$ and of thermal considerations means that a machine produces a specific torque (in units of N-m/kg or N-m/m^3), with a continuous rating determined by steady-state cooling capacity and a peak rating determined by hot-spot temperature. The converse means that a desired motor torque rating implies a motor mass. If the torque requirement can be dropped in half, the mass can also drop in half.

It is important to recognize that the specific force is not a function of motor speed: a given motor has a pre-determined continuous and peak torque rating, which in principle can be delivered at any speed. Mechanical considerations of rotor structural strength and bearing capability limit the running speed of any motor. Structure is the key limiting factor for IPM motor designs. For other types of machine, structure is a less critical issue. The machine designed for the GM EV1, for example, reaches 15,000 RPM [13].

Specific power in a machine is the product of specific force times speed. If a machine is permitted to operate at increasingly high speed, the specific power increases. For example, a machine with a rated continuous torque of 300 N-m can deliver about 37 kW continuously at 1200 RPM – and 113 kW at 3600 RPM. Motor mass tradeoffs can be obtained by trading torque and speed ratings. This is well known in the aerospace industry. In jetliners, for example, it is common to spin electric generators from turbojet engines at 24000 RPM. A small machine with a rating of just 30 N-m can deliver 75 kW at this speed.

Notice that the same general behavior is well established for internal combustion engines (ICEs): to first order, engine force and torque are determined by size and power is determined by speed. This is more approximate than for electric motors, since the useful speed range of an ICE is relatively limited. Even so, extreme high power levels, such as those in race cars, are produced by spinning the engine much faster than normal.

Unfortunately, much past practice in traction system design has treated motor output power as a limiting factor rather than the torque. This often leads to oversized machines. In a typical system, the oversizing is reflected in the use of field weakening for high speed operation. This technique deliberately reduces **B** in a machine, reducing the force density to match the more limited requirements of a system. By definition, field weakening produces less force than is possible.

In nearly any transportation application, the force density characteristics of motors and engines rule out direct drive of a vehicle axle. For example, a typical passenger car has peak axle torque requirements on the order of 1800 N-m. An electric motor capable of delivering 1800 N-m, even for a short peak interval, is heavy and large. A much better approach is to provide a gear ratio. For example, an overall drive ratio of 6:1 allows a motor with rated peak torque of 300 N-m to deliver 1800 N-m at the axle, and reduces motor mass by a factor of 6. In general, the highest possible gear ratio leads to the lowest motor mass.

The drive ratio cannot be made arbitrary high. The desired top speed of the car must not yield excessive motor speed. There are conflicting requirements: a high gear ratio is desired to deliver high axle torque while a low gear ratio is desired to achieve high speed. With electric drive, a simple alternative is a two-speed (or more) gearbox. Only a few ratios are needed because of the inherent wide speed range of the machine. This opens the possibility of simple mechanical shifting structures that give a choice of just a few fixed ratios. For example, a sun-planet gear set such as that in the Toyota Prius can be made to deliver multiple ratios depending on whether the outer gear is locked or rotating. Multiple gear ratios can lead to dramatic reductions in motor mass requirements.

Consider the following design example:

-- A motor vehicle requires 2000 N-m of axle torque to start on a steep incline when fully loaded. The maximum continuous traction power is required to be 50 kW, which is needed to achieve a top speed of 40 m/s. The tire radius is 0.3 m. A single fixed gear ratio is to be used. The motor to be used can spin safely at speeds up to 12000 RPM. It has specific continuous torque of 2 N-m/kg and peak torque of 6 N-m/kg.

- First consider a machine with a base speed of 1800 RPM that is to be used in field weakening above this speed. This represents conventional practice. For the given tire radius, 40 m/s corresponds to an axle speed of 1275 RPM. To keep the motor maximum speed below 12000 RPM at vehicle top speed, the highest allowed gear ratio is 9.42:1. This motor must produce 50 kW continuously. Since field weakening yields a constant power characteristic above base speed, the motor must be rated for 50 kW at all speeds about 1800 RPM. This yields a continuous torque rating requirement of 265 N-m. The 2000 N-m incline torque requirement yields a peak torque need of (2000 N-m)/9.42 = 212 N-m. In this case, the power rating dominates. The necessary motor mass is (265 N-m)/(2 N-m/kg) = 133 kg.

- Next consider a machine with a base speed of 12000 RPM, not used with field weakening. As above, the maximum gear ratio is 9.42:1. This motor must produce 50 kW at 12000 RPM, which yields a continuous torque rating of 40 N-m. The incline torque requirement again yields 212 N-m, which dominates in this case. The necessary motor mass is (212 N-m)/(6 N-m/kg) = 35 kg. The motor can be made lighter by a factor of about 3.8 by avoiding field weakening.
- Now consider allowing a two-speed gear ratio rather than a single speed. The maximum ratio allowed for high speed is still 9.42:1, but a higher ratio can be used to improve the torque a low speed. For example, if low gear has a ratio of 16.7:1 and high gear has a ratio of 9.42:1, then the continuous and peak torque requirements are mutually consistent. A motor with continuous rating of 40 N-m will meet all the specifications. Its mass is only 20 kg.

In general, motor mass can always be reduced when field weakening is used sparingly and multiple gear ratios are available. In contrast to ICEs, in which many gear ratios are desired to keep the engine operating close to a pre-determined set point, the electric traction case requires only a few ratios and uses a wide motor operating range. There is diminishing return to more than a few gear ratios.

One argument for avoiding multiple gear ratios is that the gear shift process might require extra elements such as clutches, transmission linkages, and other processes. In the case of a hybrid electric vehicle, this complexity can be avoided. Since the dynamic torque response of an electric motor is very fast, the inverter can adjust motor torque rapidly to facilitate the gear shift process. In a typical process, when the car is to up-shift, the sequence is as follows:

1. Drop motor torque to zero to allow gears to unmesh.
2. Alter the motor speed down to match the expected speed in the higher gear.
3. Drop the motor torque to zero to allow gears to remesh.

4. Raise motor torque back to the level commanded by the driver.

This process has been implemented in a previous vehicle design [8], and can perform smooth shifts in time intervals on the order of 0.2 s. In the version in [8], the shift command is given by the driver, who moves the shift lever without the need for a clutch. In a more practical vehicle, the shift can be activated by a solenoid or similar mechanism. This generates an "automatic gearbox" with the low loss characteristics of a manual transmission but the smoothness and flexibility of an automatic transmission.

Research is needed on good ways to implement simple limited-ratio gearboxes that support high drive efficiency. A two-speed or three-speed gearbox can reduce motor mass substantially without compromising vehicle performance. Since a gearbox is needed in any case, it is appropriate to identify multi-speed techniques that facilitate system-level cost and mass reduction. Research along these lines could be conducted by a joint industry, national lab, and university mechanical engineering team. The potential benefits are strong and could bring immediate performance improvements in hybrid vehicle systems. Given the solid existing technical base, an intensive one-year joint project should be able to make significant progress on this topic. It appears to be an excellent way to involve automotive industry development engineers.

Fundamental understanding of dynamic capabilities and energy tradeoffs in fuel cells

Data are just beginning to emerge on dynamic capabilities and issues in fuel cells. This aspect of fuel cell performance is critical to system development. For example, if a vehicle fuel cell can ramp power over most of its range on time scales of 0.1 s or less, it is possible to avoid most energy buffering. The fuel cell could cover accelerations and other fast changes. Only the very brief needs of aggressive acceleration and regenerative braking would benefit from energy buffers. Fast performance therefore tends to eliminate batteries in favor of ultracapacitors. Past data seem to suggest that slew rates are on the order of 20 s or more rather than 0.1 s or less. Slow times such as this require substantial energy storage in batteries. The added demands on batteries, combined with the high power levels that are needed, reduce system efficiency.

The rates are linked to the nature of the fuel cell and its system-level process. For example, reformers that produce hydrogen tend to respond slowly. Fuel flow and pressure systems respond more quickly. The internal dynamics of the fuel cell itself are limited by chemical diffusion and delivery of reactants. Unfortunately, present information about dynamics is limited. How quickly can a PEM respond in a practical system? Are there extra losses or stresses associated with fast power swings? If so, what are the tradeoffs and how can a system be designed for good interactions between batteries, fuel cells, and ultracapacitors? Can the slew rates be adjusted in a useful manner?

An additional open question is the tolerance of fuel cells for current ripple. Fuel cells have substantial internal capacitance, so they have a "self-filtering" capability. It is unknown to what degree this capacitance can be integrated with power electronics design. For example, does this capacitance bring with it failure modes similar to those in electrolytic capacitors? If the capacitance can serve as part of converter filtering, this could have substantial advantages for system cost and performance.

There is an urgent need for fuel cell manufacturers to work with national laboratories to generate dynamic performance information. The power slew rates, ripple current capacity, and dynamic capacitance values are not known over the ranges of interest. Tradeoffs that may work against high power slew rates or the use of fuel cell capacitance for filtering need to be identified and characterized. This is an urgent need that prevents proper analysis of design tradeoffs in fuel cell vehicles. Until it is fully addressed, all designs must be considered speculative.

A project to generate the necessary data would require at least one fully functional fuel cell at the appropriate power level, including auxiliary support equipment. Given the need for a working fuel cell, this is likely to be a costly project that would involve a small engineering team from a fuel cell manufacturer, working in collaboration with a national laboratory project leader. The results will translate rapidly into savings in energy storage elements and power electronic converters. This is because overdesign of storage and processing subsystems can be avoided with the proper data in hand. The issues can be summarized:

- From an electrical system design standpoint, information is lacking to help formulate dynamic energy tradeoffs in fuel cells.
- Constant fuel flow yields high dynamics at the cost of efficiency. Constant pressure may work better but could have diffusion rate limits.
- A slow fuel cell (minutes) requires batteries for energy buffering.
- An intermediate fuel cell (seconds) requires ultracapacitors or batteries.
- With response times of 0.1 s or better, it is possible to skip most or all energy storage and eliminate a tremendous range of costs.
- The topic could be well-suited to national laboratory contributions.

Package and device integration

Integration is widely accepted as an important factor for cost-performance improvement in power electronic systems. The integration step itself may not reduce device costs, but improvements in thermal capability, reliability, manufacturability, and electromagnetic interference are expected to be considerable. The best work along these lines can be found in a few university laboratories [14]. There is probably extensive work in industry as well, but it is not generally available for public scrutiny. Recent developments for semiconductors include better packaging approaches for double-side liquid cooling. Recent developments in other components are generating new ways to integrate capacitors and inductors together into improved filter structures.

The packaging in a modern hybrid electric vehicle is often "triple enclosure" from the power semiconductor viewpoint. The semiconductor die itself is embedded on an insulating substrate and enclosed in its own package. Then this package is mounted on a heat sink and further enclosed in an outer box. The box itself is enclosed under the car hood or within some metal structure. The multiple enclosures limit heat flow, add weight and cost, and may be redundant in terms of protection. A more effective approach is needed at the system level.

It is important for the FreedomCar program to be involved in further development of integrated power electronics components. There is an opportunity to bring together industry engineers working at a pre-competitive stage to gain synergy and overcome fundamental problems. University work would benefit from modest funding, perhaps two students and two faculty members over the next five years, as part of an ongoing effort to improve integration.

Controls that support "soft-bus" or other alternative designs

A hybrid vehicle system that is *not* based around a constant operating bus voltage could provide significant advantages. Such a configuration may be substantially more tolerant of the highly variable voltage from a fuel cell or ultracapacitor. It would, however, be a fundamental departure from present system design practice. If a two to one voltage range could be tolerated without performance degradation, then ultracapacitors could define the bus level and at least one bidirectional dc-dc converter could be avoided. The recently introduced impedance source method (termed *Z-source* in the literature) [15] is an especially interesting approach that deserves further study and development.

A more revolutionary change would be to consider a high-frequency ac bus rather than a dc bus for power distribution. High-frequency ac systems have been deployed in aerospace and marine power systems for a long time, and have been studied intensively for spacecraft and advanced aircraft applications. They offer advantages of convenient interfaces, simple voltage transformation, and enhanced protection compared to dc systems. A highly variable dc voltage configuration would result in oversized switches to manage the necessary extra current ratings, while an ac system would use inverters in place of dc-dc converters for fuel cell interfaces. The cost savings in terms of reduced conversion stages could more than offset extra expense in devices. This type of project is more directed toward possible future breakthroughs. It would be worthwhile to have a graduate student study this issue for a year in a university setting to determine the possible benefits.

Dynamic system simulation that identifies specific losses and short-term energy tradeoffs

There is an urgent need for dynamic system-level simulation to support detailed analysis of design tradeoffs in a hybrid vehicle system. Present tools, notably the HEV Advisor software [1, 3], provide an excellent basis for general comparisons based on steady-state effects. A simulator that is based on steady-state models of the power electronics and machines cannot capture extra losses in switches during rapid battery voltage droops. It is also difficult to ascertain the possible effects of fuel cell dynamic performance at the system level with the existing tools.

On the other hand, a detailed dynamic simulation is complicated and slow, and is not well suited to general comparisons over extended drive cycles. Thus a dynamic simulation supplements existing tools but does not replace them. Detailed simulation provides data about such issues as tradeoffs between MOSFETs and IGBTs, losses as a functions of switching frequency in magnetics, reduced output torque capability of electric machines caused by voltage droop during acceleration, losses as a function of power slew rates for ultracapacitor interfaces, and similar fast effects in hybrid vehicle systems.

There is existing progress toward dynamic simulation [2], and this report has described the most recent work and provided simulation examples. This work could provide a basis for joint efforts between university researchers and national laboratory personnel to bring about a complete practical simulation system that could be distributed. Estimated effort would involve two students, a faculty member, and a national lab expert, over a twelve month time frame.

Conclusion

Power electronics technology is a dominant factor in the development of hybrid and fuel cell vehicle systems. When three vehicle configurations presented here are compared, it is clear that the power electronics subsystems share many common elements. If present practice of building a system around a fixed dc bus voltage is retained, it is possible to identify common traction inverters, self-contained ultracapacitor interfaces, specific energy storage requirements, and other near-standard power electronics elements. Progress is limited, however, by costly semiconductor packages, other materials issues, and even the challenges of establishing a standard fuel cell dc bus voltage. A list of eleven research needs, including these aspects, has been established and discussed.

One key area that has not been addressed in prior research is the design of the traction unit as an integrated subsystem. The physics of electric machines is such that a given type and mass provides a specific rated force. The power density can be increased as desired by operating at higher speeds. An electric traction motor can be designed in conjunction with a selectable gearbox to reduce mass without compromise in performance. Similar efforts are well known in aerospace and marine applications, in which higher operating frequencies and speeds yield small machines with high power capability.

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