The Hybridization of a Formula Race Car

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Abstract—**Hybrid electric vehicles are advantageous under formula racing rules, when allowed. A series hybrid drive train was installed in a Formula SAE car, using off-the-shelf engine, generator, ultracapacitors, and ac motor drive. A dc-dc converter was developed to charge the ultracapacitors with constant power at varying voltage. A 75 m acceleration run is completed in 6 seconds. This is slower than the predicted 4.2 seconds in part due to tires slipping.**

Keywords—hybrid electric vehicle; formula racing; ultracapacitors; series hybrid; induction machine.

I. INTRODUCTION

Formula race cars are designed for maximum racing performance within specific restrictions; formula competitions involve both driving and engineering. For example, in the "Formula SAE" competition organized by the Society of Automotive Engineers for college students, a key restriction is that all the air entering the engine must pass through a 20 mm diameter orifice in a restrictor plate [1]. This serves the purpose of limiting the maximum power that any competitor's engine can produce, thus keeping speeds to reasonable levels, and of challenging teams to maximize performance within this constraint.

In this paper we explore the potential of hybrid gas-electric propulsion for a formula competition, and report the results of converting the power train of a car that was originally built for a Formula SAE (FSAE) competition to a hybrid. While this work was in progress, the FSAE competition rules were changed to disallow hybrids that use on-board energy storage [1]. Thus, the car built conforms to the spirit of the original rules, but violates the present rules. We hope that future competitions which allow hybrids will be established in order to spur innovation in hybrid drive trains. Implications of the rules of future competitions are discussed in Section IV.

A. Hybrid advantages for formula racing

The Formula SAE rules specify an engine inlet restrictor plate with a 20 mm orifice to effectively limit peak power from the engine [1]. A hybrid system with energy storage is capable of delivering peak power to the wheels in excess of the peak power from the engine, thus increasing acceleration. A hybrid can be configured such that the restrictor-limited power becomes average power, rather than peak power. This is because the hybrid can be designed to allow constant operation of the engine at full throttle ("up against the restrictor") and at the optimal engine speed for maximum power, independent of vehicle speed, and even during braking. In typical operation in a race, the conventional car is at full throttle only during acceleration or at top speed (a Formula SAE car is not intended to be operated at top speed), and only at the optimal engine speed a fraction of this time. In addition, regenerative braking can be used to recover additional energy, effectively increasing the average power available for the motor.

In this paper, we discuss the selection of the hybrid configuration to most fully realize these advantages (Section II), describe the design of the power train using the selected hybrid configuration (Section III), report results of testing the vehicle (Section IV), propose improvements (Section V), and discuss the implications for future designs and competition (Section VI).

II. SELECTION OF HYBRID CONFIGURATION

Hybrid electric vehicles are traditionally classified as "series" and "parallel"; new variations on these ideas have been called "series/parallel" [2,3]. Many of the advantages and disadvantages of these configurations are the same for formula race cars as for general-use vehicles, but a few key differences led us to choose a series hybrid.

A series hybrid has many disadvantages: It requires two electric machines (motor and generator), with the motor sized to be able to deliver the full peak propulsion power required and the generator sized for average power, whereas a parallel hybrid requires only one machine that is used as both motor and generator. Furthermore, this machine is smaller than the motor in a series hybrid, since it needs only supply the difference between the required peak propulsion power and the available engine power. A series hybrid also has the efficiency disadvantage that all the power must pass through two electric machines and through the power electronics used to control and drive each.

However, a series hybrid also has significant advantages. The engine need only operate at a single speed and torque, allowing optimization for efficiency, emissions, and/or power. With some electric motors, a fixed gear ratio can be used, and the resulting weight savings at least partially offsets the extra weight of the electric machines. And a large motor enables regenerative braking at the same high power level as acceleration.

In the case of a formula race car, under the original FSAE rules, peak and average power considerations trumped efficiency or emissions considerations. Thus, the efficiency disadvantage of a series hybrid is discounted. In addition, the control design is simplified because the engine and generator can be operated at a fixed speed and torque whenever the energy storage is not full. Thus we chose a series hybrid for our first car. We hope that future competition in hybrid formula cars will facilitate further exploration of the tradeoffs in different types of hybrids.

III. DESIGN OF A SERIES HYBRID

Because we developed the hybrid formula race car by modifying a convention formula car from a previous FSAE competition, the design choices were limited to the drive train. Where possible, commercially available components were used, and in many cases, cost and availability became a deciding factor; future iterations on the design could include optimizing components for this application.

Once the series hybrid configuration was chosen, the next major choice was the energy storage medium. The primary candidates are batteries and ultracapacitors. Although batteries are used in almost all present production hybrid vehicles, ultracapacitors offer higher power density per unit volume or per unit mass, and higher efficiency [4]. Their disadvantage is lower energy density. The relative importance of energy density and power density depends on the particular competition events. In the FSAE competition, the events require short-term acceleration for times of three to ten seconds. For example, a 75 m acceleration run is typically completed in 4 to 5 s by a high-performance car. This is exactly the range in which ultracapacitors excel, so the choice was clear: 130 2.5 V, 2700 F ultracapacitors (Maxwell PC2500) were connected in series for a total of 325 V and 680 kJ of usable energy, more than enough for two acceleration runs.

One disadvantage of the ultracapacitor energy storage system is that the capacitor voltage varies over a wide range as the capacitors are charged and discharged. Fortunately, the energy is proportional to the square of voltage, so most of the energy storage occurs over a relatively small voltage swing near maximum voltage. The system architecture can use a dc-to-dc converter between the ultracapacitors and a constant-voltage dc bus from which the motor controller runs, or the motor drive system can be designed to operate over the full range of capacitor voltages. Even using off-the-shelf components, we were able to use a range of 200 to 325 V without the extra dc-to-dc converter, which allows use of 62% of the 1.1 MJ theoretical energy capacity of the ultracapacitors, which is still more than enough for two acceleration runs.

An ac induction motor was chosen for its ability to provide near its maximum power over a wide range of speeds. The motor drive system chosen (Solectria AC55) has a rated output of 78 kW peak and 34 kW continuous, a maximum torque of 240 Nm, and weighs 122 kg. This weight is a large portion of the overall vehicle weight—design of a lighter-weight machine optimized for this application could improve performance significantly. The controller in this drive system provides optional regenerative braking controlled through the accelerator pedal—as the pedal is released, it passes through zero drive power and then regenerative braking is applied and increased, reaching maximum when the pedal is fully released.

The high torque and wide speed range of this motor allow the use of a single gear ratio, chosen as 5:1. This was implemented with a simple roller-chain drive with 60-tooth and 12-tooth sprockets.

The power delivered from the engine and generator becomes important only for longer duration competition events. Simulations of the state of charge during these events showed that only 10 to 15 kW is needed. For initial testing, an off-the-shelf 206 cm^3 displacement internal combustion engine rated for only 4.1 kW was used. We plan to ultimately use a higher-power engine, but started with this one because it was immediately available. This choice only constrains the average power delivered to the wheels, not the peak power available.

A permanent-magnet brush motor was used as the generator. A permanent-magnet machine allows high efficiency at one operating point, and this machine needs to operate at only one torque/speed point. A brushless machine's advantages of higher efficiency and lower maintenance were not our highest priorities, but could be opportunities for future improvement.

Interfacing the generator to the batteries required a dc-to-dc converter, since the generator must be operated at constant output voltage to maintain constant speed and torque and maximize the power output of the engine, but the capacitor voltage swings widely. This converter is sized for the 4.1 kW power of the engine, and thus is much smaller than a converted sized to handle the 78 kW power of the electric motor. Off-the-shelf dc-to-dc converters usually have feedback control to maintain the output voltage at a constant value. In this application, we want to allow the output to vary while we maintain constant input voltage and current. Thus, an off-the shelf converter could not be used, and a pulse-width-modulated (PWM) boost converter was designed specifically for this application, to convert the 48-V output out of the generator to the capacitor voltage, which ranges from 200 to 325 V in normal operation (and lower for initial charging). The control could theoretically be designed to maintain constant input power, voltage, or current. However, a slight error in voltage would lead to a large change in current, and the correct voltage can be expected to vary with any slight variations in engine speed, so current and power regulation are better choices. Current regulation was chosen because it is simpler to implement. Input current was monitored by a hall-effect sensor and compared to a reference; the voltage-regulation circuitry in a standard PWM IC (UCC25701) was used to control duty cycle to effect the regulation.

The converter operated at a 21 kHz switching frequency, and used an IGBT-diode module (IR 50MT060ULS) for the main power devices. 60 μF of polyester film capacitors were used at the output in parallel with the ultracapacitor stack to provide a low-inductance path for high-frequency currents.

The complete vehicle (Fig. 1), including the drive-train components described above, weighs 440 kg. This is heavier than a typical FSAE car, but we nonetheless expected competitive acceleration. A simulation based on the peak-power torque-speed characteristics of the motor is shown in Fig. 1. The motor is initially constrained by its maximum torque but transitions to a maximum power constraint after 1.8 seconds. We assume that the peak rating, rather than the continuous rating, is the relevant constraint for this short-term use, based on the large thermal mass of the machine. The vehicle completes the 75 m run in 4.2 seconds, reaching a top speed of 30.4 m/s (68 mph), as shown in Fig. 2.

Figure 1. Completed vehicle. One of two ultracapacitor banks is visible to the driver's right.

IV. RESULTS

A. Acceleration Testing

Acceleration was tested on a 75 m run, without the engine/generator running. Trials were unfortunately all on at least slightly wet pavement, and initial acceleration was limited by tire slippage. The best recorded time was 6.19 seconds as recorded by a stopwatch operated by hand, or 5.97 seconds from data extracted from photographs taken every 1/3 second. Speed data from these two measurements is shown in Fig. 3. The divergence during the first few seconds is due to the tires slipping. Although the performance we measured is very good—better than some FSAE competition cars' performance on a dry track—it falls somewhat short of the performance we predicted. In addition to the issue of the wet pavement, we believe that the motor controller may be backing off from the rated peak power before any thermal limits require it to.

A comparison of the energy used from the capacitor in an acceleration run (218 kJ) to the final energy stored in the kinetic energy of the car (103 kJ), indicates an efficiency of only 47%. Our models of rolling resistance and air drag indicate that only 3% of the acceleration energy should be lost to drag and rolling resistance, and specifications for the motor and controller indicate greater than 85% efficiency for almost all operating points, so we believe tire slippage is responsible for most of the energy lost.

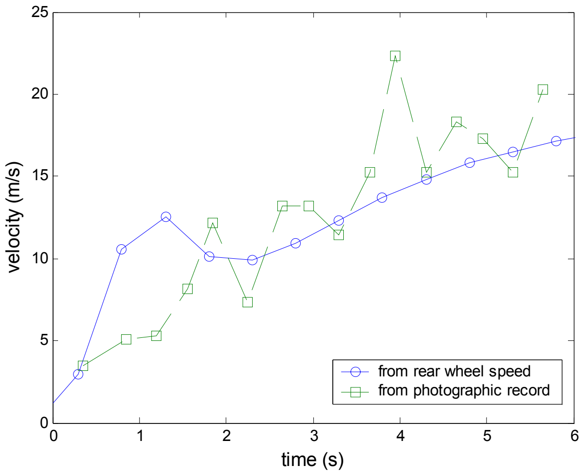

Figure 3. Velocity during an acceleration run measured from rototaional speed of the rear wheels (o) and from a photographic record (□). The two data sets diverge at the start due to the tires slipping on wet pavement.

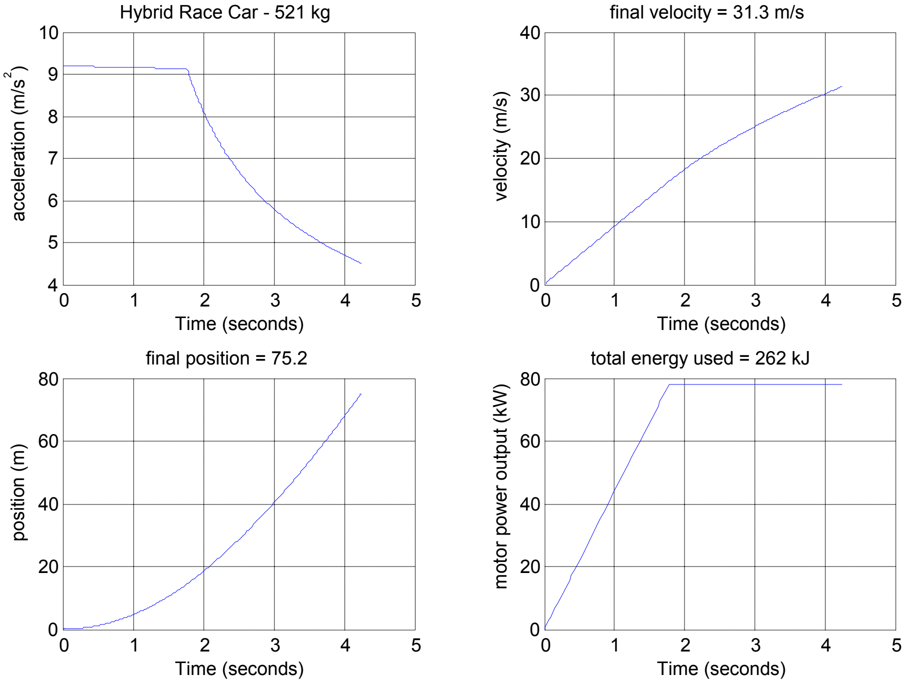

Figure 2. Simulated performance for a 75 m acceleration run.

B. Regenerative Braking

The electric motor could provide enough torque to make the wheels slip in both acceleration and regenerative braking. However, the tendency was more pronounced in braking, presumably because braking shifts weight to the front wheels, while the regenerative braking is applied only to the rear wheels. The resulting skidding limits the regeneration power available, but more importantly, it throws the car into oversteer instability. In practice, we found the regeneration as implemented almost unusable, and it would certainly be ineffective, if not dangerous, in a racing application.

V. FUTURE WORK

Although much testing of the prototype vehicle and its components remains to be done, our initial testing highlights the importance of improvements in several areas.

Our tests clearly indicate that the present regenerative braking is not adequate for use on a race course. A standard rear-wheel drive, single-motor drive train works well for typical FSAE cars because the functions of acceleration and deceleration are independent of each other (neglecting a small amount of engine braking). With regenerative braking, however, connecting the motor only to the rear axle severely limits performance.

Strong regenerative braking on only the rear axle upsets the front/rear brake bias and wreaks havoc with the tires' road-to-rubber friction circles, making the car prone to oversteer instability. The optimal solution would be to modify the drive train to couple all four wheels. This could improve acceleration, but would definitely improve handling during “trail-braking” while entering corners.

There are also energy efficiency considerations: any race car benefits from better efficiency but hybrids can derive additional advantages from efficiency improvements, because these would allow for reduction in size and weight of the generator and onboard energy storage system. Since the front brakes do more of the work to stop the car, ignoring the front brakes for regenerative braking sacrifices a significant amount of potential regenerative energy capture. Regenerative braking also reduces the workload on the vehicle's mechanical brakes, lowering the heat dissipation requirements. This reduces the potential for brake fade and could also allow a reduction in the mass of calipers and rotors.

The hybrid drive train could be extended to all four wheels via a mechanical AWD solution, but more advantageous would be a four-wheel independent electric motor drive system. With the proper control system, such a drive train could balance the acceleration and brake torque dynamically for each wheel to improve vehicle performance in any situation.

Optimizing the motor control strategy offers opportunities for performance improvement with few hardware changes. Ensuring that the controller aggressively keeps the motor at its (thermally-limited) peak torque or power is important to realize its full capability in race events. Although strong regenerative braking requires coupling the front wheels to one or more electric machines, useful regeneration may still be possible with smaller torque applied through the present system, used in conjunction with strong mechanical braking primarily on the front wheels. The motor control could also be adapted for acceleration events by allowing the driver to establish a high rotor flux in advance of commanding any torque, in order to reduce the time required to increase the torque from zero to maximum.

VI. OUTLOOK

This work has confirmed that within the normal constraints of formula racing, a hybrid drive train can confer tremendous advantages. This might be considered to be evidence validating the choice of the FSAE competition organizers to effectively prohibit hybrid vehicles. A well-designed hybrid might out-perform any conventional car, and might circumvent the intended effect of the formula in preventing excessive and potentially unsafe speeds.

But the broader implications of the choice to prohibit hybrids should be considered carefully. Waiting lists for hybrid vehicles attest to consumer acceptance of and demand for hybrid vehicles, which will become increasingly important as engineering graduates enter the workforce. Excluding this important new technology inhibits students from getting first-hand experience with it. More broadly, and perhaps more importantly, the FSAE competition is now well enough established that true design innovations are few and far between. As a result, an increasing share of the work involved is vehicle construction rather than innovative design engineering.

A competition that allowed hybrid drive trains would open the door to a wide range of innovations, and would expose students to technology that will be increasingly important to the auto industry. With the hybrid race car, students can be challenged with drive motor design, high-power electronics systems, four-wheel drive concepts, control design, regenerative braking systems, human factors design in braking with a mixed system, advanced closed-loop engine controls, etc. Not only does this experience benefit students, and benefit the automotive industry by helping educate students in the technology they will need to work with, but there is also a considerable possibility for technical advances that could ultimately benefit society.

To realize the advantages of a formula competition that allows hybrids, FSAE could modify their rules to allow hybrids in the main competition, a separate class could be established within the FSAE competition, or an entirely separate competition could be established. In any of these cases, we would recommend that, at least after a hybrid has been able to demonstrate that it can out-perform a conventional vehicle with the same restrictor plate, hybrids should be subject to more restrictive rules, in order to make the competition between hybrids and conventional cars less one sided and more interesting in competitions that include both, and to limit the speed of hybrid vehicles to improve safety.

Possible rule modifications for hybrids could include the following: The restrictor plate could be required to have a smaller orifice and/or the engine displacement could be limited to a relatively small size (e.g., 250 cm^3). This leaves open the possibility, however, that the energy storage and electric motor could accelerate the car to excessive speeds, and some restriction there might also be appropriate. One option would be to specify an electrical resistor, analogous to the restrictor plate, which, in conjunction with a maximum voltage specification (which could improve safety in and of itself), would effectively limit power. However, a restriction on maximum energy storage capacity might be preferable because it would be less artificial, and more akin to the design challenges faced in the design of practical vehicles; and because it would indirectly limit the cost of the energy storage, thereby making the competition accessible to more teams.

Without a limit on energy storage capacity, one competition strategy would be to maximize energy storage and start a given event with more energy stored than at the end of the event. At one extreme, one could use a purely electric vehicle, charged prior to the event. In designing the competition, options would include allowing this as a legitimate strategy, enforcing a requirement that the vehicle must return the energy storage system to the initial state of charge at the end of the event.

VII. CONCLUSIONS

We have shown that hybrid electric vehicles can offer significant advantages under formula racing rules, unless, of course, those rules prohibit hybrids (or effectively prohibit them by proscribing energy storage). A series hybrid drive train was installed in a Formula SAE car. A 206 cm^3 displacement engine drives a permanent-magnet brush generator. A PWM boost converter was designed to charge ultracapacitors from the generator output, using current feedback to maintain constant input current (and thus constant loading of the engine) despite variations in ultracapacitor voltage. The ultracapacitors feed an off-the-shelf ac motor drive system that drives the wheels through a constant-ratio roller-chain transmission. Expected performance includes a time of 4.2 seconds for a 75 m acceleration run. Initial testing showed that the run could be completed in 6 seconds.

Although present FSAE competition rules exclude high-performance hybrids, we argue that student competitions allowing hybrids would provide students with a true opportunity for creative design experience, prepare them for the future of the automotive industry, and foster innovation. Because of the high performance possible from a hybrid, it may be desirable to create more restrictive rules for hybrids, such as smaller engine displacement, a smaller restrictor-plate orifice, an electrical resistor in conjunction with a voltage limit, and/or a limit on energy storage capacity.

ACKNOWLEDGMENT

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