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Control and energy management strategies for a novel series hybrid

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Abstract

In this work a novel series hybrid powertrain concept is presented. The concept removes the requirement for a power electronic converter to manage the state of charge of the accumulators by controlling the power flow between the generator and accumulator. Instead, the engine and generator are directly coupled and the state of charge of the accumulators is maintained by controlling the speed and power output of the engine to control the power flow to the accumulators. Results are presented from a proof-of-concept system that was built for a vehicle with a target peak power of 60kW with supercapacitors. Models are also presented comparing and contrasting a battery version with the supercapacitor version for a Formula Student vehicle. The powertrain is particularly suited for applications which have very high torque requirements, and hence the use of a mechanical gearbox introduces significant cost & weight, and is also ideally suited for applications where power needs to be distributed throughout an application to multiple locations, and hence multiple mechanical linkages would normally be required. The supercapacitor version is most suited to applications with high peak to average load ratios and noisy load cycles, and the battery version could be seen as a low cost route to range extend a battery electric vehicle.

Keywords: HEV (hybrid electric vehicle), PHEV (plug in hybrid electric vehicle), EDLC (electric double-layer capacitor or supercapacitor), battery, EREV (extended range electric vehicle)

1 Introduction

The introduction of commercially available hybrid electric vehicles such as the Toyota Prius in 1997, more recently battery electric vehicles such as the Nissan LEAF in 2010, and the anticipated launch of hydrogen fuel cell vehicles by many manufacturers in 2015, heralds a period of transition in the automotive industry. The transition is predicted to take decades, and at present not enough is known to predict which technology will be the winner [1]. As such many competing technologies are being developed. Hybrids can both be considered a transition technology but also the end-game for certain applications, where the need for high energy density chemical fuels will always be a significant advantage.

The hybrid concept presented in this paper is a series hybrid where the internal combustion engine (ICE) is decoupled from the wheels, and is connected directly to an electrical generator (EG) at all times, via a fixed ratio one-stage transmission. The output of the generator is connected directly to the accumulators. Because there is no power electronic converter to control the flow of energy into the accumulators, the output of the generator must be DC. The generator must therefore be either a brushed DC machine or an AC machine with a rectifier on the output [2]. The system described here used a brushed DC machine connected to a bank of supercapacitors with only a contactor installed between the generator and accumulators in order to break the circuit during start-up and shut-down or during emergencies. A schematic diagram of the system is shown in Figure 1.

The hybrid configuration relies upon a DC output of the EG being coupled to DC Faradaic or non-Faradaic accumulators, i.e. batteries or supercapacitors. Whatever voltage the accumulators are at, the EG must be spinning at a speed proportional to that voltage, dependent upon its voltage constant, as described by equations 1 and 2. The ICE being coupled to the EG must also be spinning at a speed proportional to the EG speed, as described by equation 3.

$$E_{acc} = E_{EG} \pm IR \quad (1)$$
$$E_{EM} = k.\nu_{EG} \quad (2)$$
$$\nu_{ICE} = k.\nu_{EG} \quad (3)$$

In the brushed DC case, no diode is installed between the EG and accumulator, and hence power can flow in either direction, depending upon the voltage difference that exists between the two.

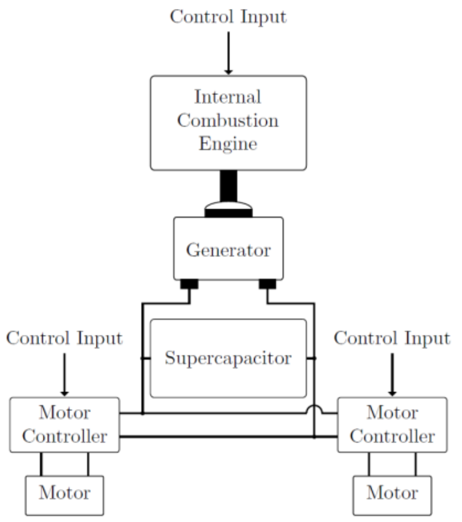

Figure 1: Schematic diagram of the series hybrid concept described in this paper, using an internal combustion engine, brushed DC electrical machine, and supercapacitors, powering two wheels with two motors and motor controllers.

In the case of a load being applied to the accumulators by the drive motors, the voltage will drop and hence current will start to flow from the EG, reducing its speed and hence applying a load to the internal combustion engine, reducing its speed in turn. The far lower impedance of the supercapacitors compared to the EG means that within the first second most of the current is provided by the supercapacitors; hence for short load spikes they will provide most of the power. However, if a sustained load is applied, then the EG will begin to provide a significant amount of current and hence reduce the speed of the ICE. In order to maintain operation of the ICE at a reasonable speed, and prevent the voltage of the accumulator dropping below that required for normal operation, the power output of the ICE is then controlled in order to maintain its speed, and hence indirectly regulate the voltage, and therefore state of charge of the accumulator. In this way, expensive and complicated power electronics can be avoided.

There will obviously be losses associated with power flowing between components, and hence an energy management strategy is important in order to minimise power flows. It is important to understand the transient behaviour of each component, whether the impedance of the accumulators or inertia of the ICE, or both in the case of the EM. It is also important to understand the nature of the application, i.e. typical load cycles. Then by optimising the properties of the three principle system components it is possible to design a system that is both efficient and stable.

The system is ideally suited for applications which may have very high torque requirements, and hence the use of a mechanical gearbox introduces significant cost & weight

The system is also ideally suited for applications where power needs to be distributed throughout an application to multiple locations, and hence multiple mechanical linkages would normally be required.

This type of system can be considered as somewhat analogous to a diesel electric locomotive, where the requirement for high torque at 0 rpm and distributed power prevents the use of mechanical gearboxes and linkages. Instead a large AC generator is coupled with the diesel engine and then the power distributed to the traction motors driving the wheels. The diesel engine in this way can be maintained at a relatively constant speed, and the power flow managed by regulating the output power of the engine.

Most systems are based upon AC generators and drive motors, and nearly all series hybrids based upon DC systems use power electronics to regulate power between the generator and manage the state-of-charge (SOC) of the accumulators, and only limited work has been conducted on so called 'passive' hybrid systems where the accumulator is directly coupled to the generator [2]. This is despite the world's first ever hybrid vehicle in 1900, the Lohner-Porsche Hybrid being of this type, and some experimentation with super-heavy tanks during WWII. However, this was probably due to the fact that practical power electronics did not exist at the time and if DC accumulators were required to store energy, then direct connection was the only practical solution. However, the various methods of controlling such systems had not been fully explored.

2 System design

The system built for the initial tests presented in this work was based upon a Swissauto SA250 SE221 21kW (28hp) 4-stroke go-kart engine with fuel injection, , an Agni 119-R axial flux brushed DC machine, and two (2) banks of Maxwell 165F at 48V supercapacitor modules connected in series, resulting in a system with a peak voltage of 96V and capacitance of 82.5F. A temporary chain drive system was used to connect the ICE to the EG. The ICE chain drive and EG system were held in a cradle designed to be either positioned on the bench or installed in the mule vehicle, as shown in Figure 2. Bench tests were performed to prove the concept by determining to what extent the controller could reliably and safely charge the supercapacitors without exceeding safety cut outs and determining how the system responded to dynamic loads. During the initial tests, the system was operated using the throttle to control the output power of the ICE. This was achieved using a proportional-integral-derivative (PID) controller where the output specified the required throttle position. In-vehicle tests were also performed on a dynamometer.

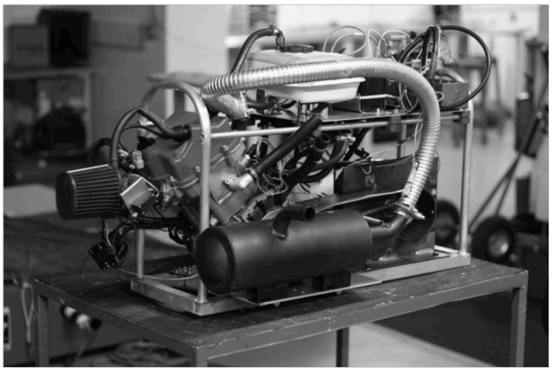

Figure 2: The ICE-EG system held in a cradle.

3 Bench testing

In the initial tests, the vehicle power demands were simulated using a 12kW load bank connected directly to the supercapacitors. The load bank was programmed to provide a very dynamic pulsed load following a square wave profile, varying between 0 kW and 12 kW at a frequency of 2Hz. The system was started from stationary but with a 40V charge on the supercapacitors. The target system voltage was set to 70V and results are shown in Figure 3.

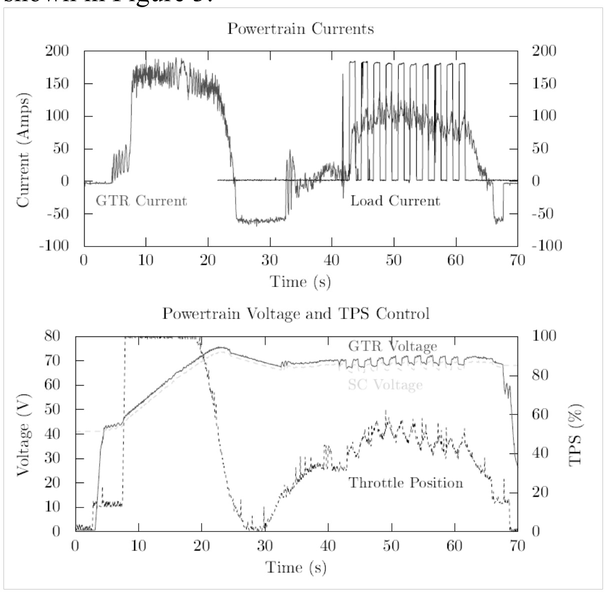

Figure 3: The behaviour of the powertrain during bench tests, during start-up, dynamic loading with a square wave between 0kW and 12kW at 2Hz, and shut-down. GTR is generator (or EG) and SC is supercapacitor.

Figure 3 shows the results of this test. At time = 4 seconds the initial starting of the engine is shown, followed by a period of acceleration to match the generator voltage with the supercapacitor voltage. Once these voltages were within 0.5V of each other, the contactor was closed and a further period of acceleration was required to charge the supercapacitors. A charging current of 150A was required for 20 seconds in order to reach the target voltage of 70V. A slight overshoot of voltage is seen accompanied by a short period of discharge from the supercapacitors back into the generator.

A pulsed load was then applied at roughly time = 40 seconds after starting the engine. During this period, it can be seen that the generator current is roughly constant, but that the load current follows the dynamic demand accurately.

The dynamic load was disconnected just after time = 60 seconds and the supercapacitor contactor opened to allow the system to be shut down. It can be seen that the supercapacitors remain charged at the end of the test. This leaves them in an appropriate state to allow the system to restart for the next test.

The intial bench tests showed that the drivetrain concept was able to deliver highly dynamic loads whilst maintaining the state of charge of the accumulators. Further to this, the drivetrain was able to deliver 12kW peak power to the load whilst the ICE delivered approximately 6kW throughout the dynamic section of the test. This shows that a drivetrain of this type would be able to deliver peak power well in excess of the maximum output power of the ICE.

The results show that during each transient the supercapacitor voltage drops during the periods of high load and recovers during the periods of no load and the controller tries to vary the throttle position to maintain the target voltage. This controller behaviour is undesirable and further work will improve the tuning of the controller.

Some overshoot in accumulator voltage was observed at times. It was suggested that this was due to the inability of the controller to vary the output power of the engine quickly enough suring highly transient events, using throttle control only. This is discussed further below.

4 Vehicle testing

For the vehicle tests, a mule vehicle was used, described in previous work [3]. The mule vehicle was a battery-electric vehicle which had been built to race in the Institute of Mechanical Engineer's Formula Student competition in 2011. The ICE-EM combination was installed in one sidepod on the vehicle and the supercapacitors were installed in a second sidepod. The target voltage for the vehicle tests was set to 88VAt this voltage the maximum energy stored in the accumulator was under 320kJ or roughly 90Wh. The mule vehicle had two Kelly PM72601B, motor controllers, powering two Agni 95R brushed DC motors as shown in figure 1.

During the vehicle testing the controller was upgraded to control both throttle and fuel injection. The latter was achieved by using the energy management controller to interrupt the fuel injection signal when it needed to reduce the output power from the ICE quickly

The vehicle was tested on a dynamometer with a drum inertia simulating a vehicle with a mass of 250 kg. The vehicle tests were designed to determine how well the drivetrain would handle the most aggressive demand likely to be placed upon the system. a series of three progressively longer acceleration events were carried out, interspersed with short coasting events. The target voltage was set to 80V.

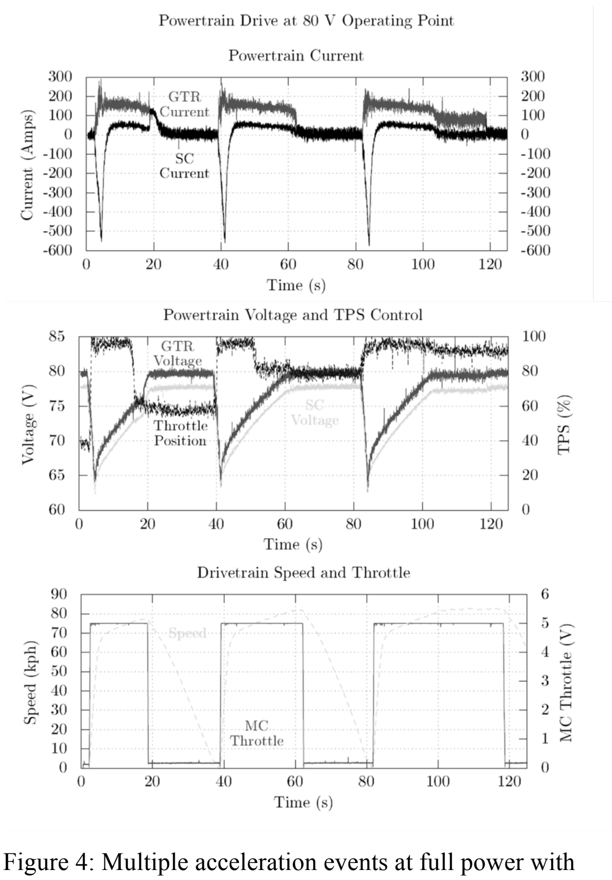

Figure 4: Multiple acceleration events at full power with a target voltage of 80V

Figure 4 shows the results of this test. The lower graph shows the periodic hard acceleration requests to the motor controller, which required an input signal between 0 and 5V, with 5V representing full power, and the speed of the vehicle rising throughout each of the events; with an initial sharp acceleration accompanied by a rapidly dropping supercapacitor voltage, followed by a slower region of acceleration when the voltage of the supercapacitor meets the input voltage of the motor controller.

At this point, the supercapacitors are no longer providing power and the only power available is that generated by the ICE-EM system, and hence the rate of acceleration is lower. The size of the supercapacitors determines when this point is reached. The periods of coasting were sufficient to give the ICE-EM system enough time to restore the voltage to target prior to the next acceleration.

Vehicle Modelling

A simulink model of the powertrain was made, which was used to predict the performance of a vehicle undergoing several dynamic events, and capable of predicting the fuel consumption and corresponding CO_2 emissions. The model was validated using the test data and was found to be able to adequately predict the current flows and voltage changes within the powertrain.

The model was used to investigate the effect of changing the size of the vehicle's electrical storage device on the vehicles performance at the Formula Student competition. Specifically the performance of seven supercapacitor bank congurations between 19.69 F and 181.82 F and five battery pack congurations between 15 Ah and 40 Ah were examined. The optimum conguration of the energy storage device for this specific application was found to be a 20 Ah battery pack with a mass of 18.6 kg. This conguration is expected to achieve a score of 558.9 out of 625 for the Formula Student events tested.

The DC machine block from the SimPowerSystems toolbox of Simulink was used to model the electric motor. The constants used in the motor model for the Agni 95-R are shown in Table 1.

Table1: Parameters used in the motor model

	Current (A) Power (kW)
Internal Resistance (R)	0.0125 Ohms
Inductance (L)	20 x 10^{-6} H
Torque constant (Kt)	0.1345 Nm A^{-1}
Voltage constant (Ke)	0.1345 V rad^{-1} s

The generator used is the Agni 119-R and has been modelled in the same way as the traction motors using the DC machine block from the SimPowerSystems toolbox in Simulink. The torque constant required by the motor model was obtained from the Agni Motors. The inertia internal resistance and inductance of the generator were assumed to be similar to the values obtained for the Agni 95-R.

The battery block from the SimPowerSystems toolbox of Simulink was used to model the lithium ion batteries, based upon the SLPB11543140H2 cells made by DowKokam using the parameters from [3], and an allowance for packaging and contact resistance, and are shown in Table 2. The model was found to match the performance of the cells to a reasonable degree for currents lower than 5C and was acceptably close for larger currents (max 10C) [3].

Table 2: Battery configurations considered

Capacity (Ah)	Weight (kg)	Internal Resistance (mOhm)
10	10.8	36.6
15	14.7	24.9
20	18.6	18.7
25	21.5	15.0
40	34.2	9.4

The motor controller is modelled as a proportional controller that controls the voltage applied to the drive motor such that the error between the motor current and the demanded current is minimised. The demanded current is set by the accelerator signal which is comes from the driver controller. The accelerator signal is assumed to be proportional to the acceleration requested by the driver. As a result the demanded current is a proportion of the maximum current of the motor controller. The maximum current was set to 1000 A.

The vehicle dynamics due to rolling resistance and aerodynamic drag using standard approaches [4]. The inertia of the vehicle and the motor were combined to provide an equivalent inertia acting on the motors, as described by Armstrong [5]. This avoided the use of a derivative block in order to find the acceleration of the vehicle, significantly reducing the computational time of the model.

A simple vehicle control system was implemented consisting of a Proportional Integral (PI) controller which aims to reduce the error between the speed of the vehicle and the speed profile provided to it. This controller is effectively the vehicles driver and its output is the accelerator pedal position. A problem encountered when implementing this was integral windup. This occured when the speed of the vehicle could not increase further but this was not known by the PI controller. This caused the integral gain to increase as the error between the demanded and achieved speed increases. This error build up resulted in a speed over run once the target vehicle speed had been reduced. In order to combat this effect anti-windup clamping was enabled which prevented the integral from summing the errors when the speed is saturated. This resulted in markedly improved speed profile tracking. This is particularly important as the error between the requested speed profile and the achieved speed profile is later used to estimate the laptime the vehicle would have achieved. However, the error introduced means that if the powertrain was not capable of meeting the desired speed profile, then the vehicle speed would start falling below the target speed. When the target speed fell below the vehicle speed, then the controller would start following the target speed again, forgetting that it hadn't travelled as far. Effectively the model would teleport the vehicle forward in space. Hence, when using this model the powertrain must be sized to meet a target speed profile most of the time to minimise this error.

The supercapacitor model was modelled as a single capacitor of a suitable capacitance and voltage using an equivalent circuit with an ideal capacitor and a series resistor. Leakage current was ignored due to the timescales of the models, and the charge redistribution effect was ignored by selecting a capacitance value representative of the typical load frequency (around 1 Hz). The constants used in the supercapacitor model are based on the Maxwell K2 series and an allowance for packaging and contact resistance are shown in Table 3.

Table 3: Supercapacitor configurations considered

Capacitance (F)	Weight (kg)	Internal Resistance (mOhm)
19.7	10	29.7
36.36	13	22.4
45.45	15	18.8
60.61	19	14.9
90.91	25	12.9
121.22	36	7.4
181.82	50	6.4

The engine was modelled using the engine's power curve at wide open throttle. This was obtained through testing using a go-kart on a dynamometer. The engine torque at each engine speed was calculated and a lookup table was used in the model. It was assumed that the torque output reduced linearly with throttle position. This engine torque was then applied to the generator model. The equivalent inertia of the engine and generator unit was calculated using Armstrong's method again [9]. This equivalent inertia was added to that of the generator and used in the DC machine block. This is possible as the engine and generator are geared together and so cannot rotate independently. When the engine power is not needed the engine is hence forced to spin at high speed as the generator will still be connected to a fully charged supercapacitor bank. This will cause large losses in the system and so was an effect that had to be included in the model.
Frictional losses in the engine and the engine efficiency calculated from the torque were estimated using standard methods [6]. Any inaccuracies in the estimation of partial throttle effciency are likely to overestimate the fuel used by the vehicle, and as the Hybrid configuration being modelled is not expected to operate at partial throttle for any significant period of time the effect on the fuel consumption results is likely to be small.

The engine is controlled by a proportional controller that aims to reduce the difference between the target voltage and the supercapacitor voltage. The target voltage has been set to 87 V in order to prevent the engine from overcharging the supercapacitors. This also allows the capacitor to store any energy recovered from regenerative braking without overcharging the supercapacitor.

A base mass of the vehicle of 220 kg was assumed, which include the ICE-EM system, the mass of the supercapacitor or battery accumulators was added to this.

The model was validated through comparison with the data from the test data shown in Figure 4, and showed reasonably good reproduction, as shown by a comparison of the supercapacitor voltages shown in Figure 5.

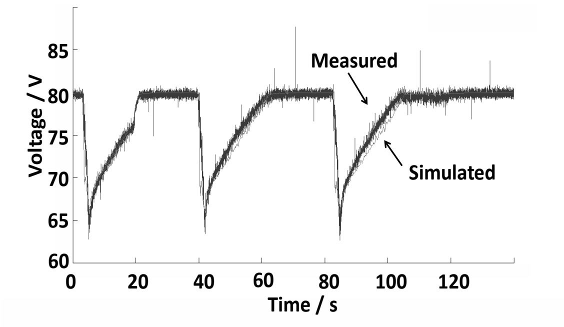

Figure 4: Comparison of simulated and measured supercapacitor voltage

Scoring System

At the Formula Student Event a vehicles success is measured by the number of points it scores in both the static and dynamic events. The model is only able to assess the vehicles dynamic performance. Of the dynamic events, the endurance event has the largest number of points allocated to it with 300 for the distance event itself. The endurance event is also used to assess the vehicles fuel economy score. This is based on the amount of CO_2 emitted by the vehicle. 100 points are awarded to the vehicle with the lowest emissions over the 22 km distance. These points are only allocated to vehicles that complete the endurance event. This means that reliability of the vehicle is paramount and a failure to complete the endurance event would mean a severe reduction in the points the team receives.

The acceleration event is a test of the vehicles acceleration and is determined from the shortest time a vehicle can cover distance of 75 metres from a standing start. There are 75 points available for this event.

The skid pad is a test of the vehicles handling and grip and involves driving the vehicle in the shape of a figure of eight in the shortest possible time. As this simulation focuses principally on the power limitations of the vehicle and in particular does not model tire traction it is not possible to estimate the vehicles performance in this event.

The sprint event involves the vehicle completing one lap of the formula student track in the shortest possible time and with the least points deductions for going of the track or hitting the cones marking out the track. There are 150 points available for completing this event.

The equations governing how these points are awarded are taken from the Formula Student regulations and are implemented within the model so is able to directly calculate to points awarded.

The model uses the data for the fastest vehicles in 2010 (the year that velocity time data for the winning vehicles was available) to represent the quickest time possible and be the input speed trace.

For the endurance event this is a time of 70.2 seconds which is the fastest lap of the endurance track completed by the AMZ Zurich team.

This time was used as the fastest time in the endurance equation. This performance is representative of the optimum performance of a formula student vehicle and it is assumed if matched would result in first place in this event.

For the CO_2 emissions equation the minimum emissions of any vehicle at Formula Student in 2010 was also by the Zurich team with their battery electric vehicle, their score of 3.264kg was used as $CO_{2.Min}$.

For the acceleration event the fastest time achieved at the formula student event in 2010 was used. A time of 4.661 seconds was achieved by the Chalmers University of Technology team.

For the sprint event a velocity time trace was created from the Zurich teams fastest lap on Youtube by transcribing the speed which was overlaid onto the video. A time of 61 second was achieved in the lap, winning the sprint event.

Model Results

Figure 5 shows the speed achieved by the model compared to the target speed. The error introduced by not meeting the target speed was accounted for by integrating the time difference between the target speed and achieved speed in order to find the distance the vehicle would not have covered at the end of the endurance event, and it was assumed that this distance would be covered at the vehicle's average speed, and this was added onto the total time taken to complete the endurance event. The same process was used for the sprint event.

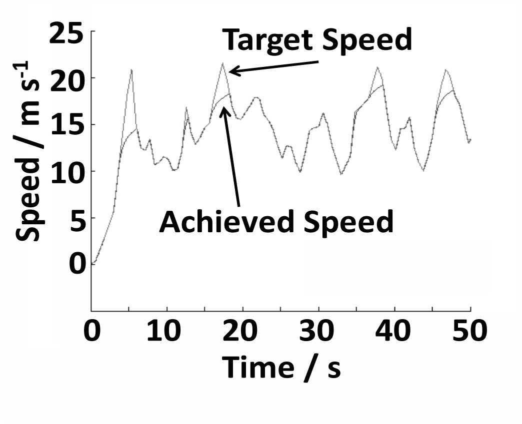

Figure 5: Example of the difference between the vehicles target speed and the speed achieved in one lap of the endurance event

The results for the 12 different powertrain configurations, 5 battery and 7 supercapacitor sizes, showed that overall the battery configuration would have marginally the best performance for a given mass of electrical storage for this particular application. However, considering the marginal difference in points it was decided to proceed with the supercapacitor version because of the reduced complexity (and hence improved reliability) and the ability to design a safer system at lower cost.

The endurance times and points for each configuration are shown in Table 4.

Table 4: Endurance times and points for each configuration

Supercapacitor		
Capacitance (F)	Time (s)	Points
19.7	1641.6	252.3
36.36	1618.5	263.1
45.45	1618.8	263.0
60.61	1618.1	263.3
90.91	1620.2	262.3
121.22	1634.5	255.6
181.82	1649.4	248.7
Battery		
Capacity (Ah)	Time (s)	Points
10	1588.8	277.5
15	1603.7	270.2
20	1605.4	269.4
25	1605.8	269.2
40	1617.9	263.4

The fuel used in the endurance event was measured and used to calculate the CO_2 emitted by the vehicle over the endurance event. This was then used to calculate the fuel economy points scored by the vehicle. The results are shown in Table 5.

Table 5: Endurance fuel economy and points for each configuration

Supercapacitor		
Capacitance (F)	CO_2 emitted (kg)	Points
19.7	5.558	76.8
36.36	5.696	75.4
45.45	5.758	74.8
60.61	5.814	74.2
90.91	5.855	73.8
121.22	5.848	73.9
181.82	5.861	73.7
Battery		
Capacity (Ah)	CO_2 emitted (kg)	Points
10	6.709	65.2
15	6.756	64.7
20	6.765	64.6
25	6.763	64.6
40	6.723	65.0

It can be seen that the supercapacitor configurations is predicted to be more efficient and produce less CO_2 than the battery versions. The only energy provided by both systems is through combusting fuel, therefore the only difference is that the supercapacitor configuration is more efficient, and this can be explained in three ways. Firstly, due to the higher efficiency of the supercapacitors when charging and discharging due to the internal resistance. Secondly, the battery configuration is faster and hence must overcome more losses. And, thirdly, the supercapacitor configuration rarely reaches its target voltage and hence the engine was running at full throttle nearly continuously and operating at its most efficient point, whereas for the battery configuration the voltage was far more stable and hence the engine throttle was often reduced.

This confirms the importance of sizing and optimising the powertrain for the typical loads of a specific application. Therefore, if the components of the powertrain are sized such that the voltage never exceeds the maximum voltage and never drops below the minimum voltage, then the engine can be run almost continously within its most efficient region.

Conclusions

This paper has presented a new concept series hydrid drivetrain using a solidly coupled ICE and generator, electrically coupled to a supercapacitor with no power electronic converters besides the motor controllers themselves. Bench testing demonstrated that the drivetrain was able to respond to very dynamic loading of the vehicle. Vehicle tests on a dynamometer demonstrated that the drivetrain was also able to handle hard acceleration events within the drivecycle. A model of the system was used to compare the supercapacitor and battery version for a Formula Student application. The battery version was able to maintain its voltage for longer and hence achieve higher speeds, however the supercapacitor version was more efficient due to both the higher efficiency of the supercapacitors but also enabled the engine to be run more efficiently, hence consuming less fuel.

The tests showed that the changing voltage of the supercapacitors affected the ability of the vehicle to continuosly accelerate at the initial high rate. This showed that the sizing of the supercapacitors to enable the vehicle to reach its top speed before the voltages balance is critical when specifying the powertrain for a given vehicle.

The paper has shown that such a simplified drivetrain is able to meet the power and energy requirements of a 60kW vehicle using a 20kW ICE. The drivetrain is very dependent on the energy management controller; however this is significantly less expensive than a power electronic converter and this simplification to the powertrain (without electronics) makes this an economically attractive design whilst still providing the performance required from a modern vehicle.

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Authors

Dr Gregory Offer is a Lecturer in Mechanical Engineering with a PhD in electrochemistry. He holds a Career Acceleration Fellowship from the EPSRC and manages a group of 10 focussing on understanding the limits of operation, degradation mechanisms and failure modes of batteries, supercapacitors and fuel cells in real world applications, and the impacts and consequences on system design, integration and control. This involves both modelling and the design of experiments in order to validate models capable of working at the extremes of operation.

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Professor Ricardo Martinez-Botas leads a group of 12 research students and research associates. He has developed the area of unsteady flow aerodynamics of small turbines, with particular application to the turbocharger industry. The contributions to this area centre on the application of unsteady fluid mechanics, instrumentation development and computational methods. The work has attracted support not only from Government agencies but also from industry. His group has become a recognised centre of turbocharger turbine aerodynamics, and more

particularly in the application experimental methods and one dimensional calculation procedures. He is also the Theme Leader for Hybrid and Electric Vehicles of the Energy Futures Lab at Imperial College.