Electrical Team Report

Dartmouth Formula Racing

ENGS 199: Hybrid Vehicle Technology

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Introduction:

At the end of the ENGS 190/290 sequence El-Myra's electrical design was reasonably complete on paper, but the bulk of our system had not been implemented. The DC-DC converter and the capacitor boxes both required a significant amount work. This report is to a limited extent a revision of our previous report. However, the latter was written to follow the grading sheet for ENGS 290 reports. We want to use this opportunity to compile a report less constrained by a grading sheet and more the type of information that would be useful to receive at the outset of the project.

To understand some of the design decisions we made, one must know some of the underlying assumptions. The budget we started with in August 2005 was a fraction of our final bottom line. Cost was therefore a major issue when we chose our motor/controller package. Furthermore, we worked under the assumption that El-Myra would inherit eSTAB's capacitors. When the budget was increased so that we could acquire a new set of ultracapacitors, we were already behind schedule. Because of this we did not extensively survey alternatives, but ordered the replacement that would require the smallest number of changes. This turned out to be the MC2600 ultracapacitor, which is simply the next generation of the model used in eSTAB. Overall, this added considerable construction time, but made the car much lighter and allowed for a more compact design.

Motor Selection:

After seeing eSTAB in action, we realized that a larger generator/engine pair was necessary to meet our endurance specification, but would also lead to a very heavy car. The AC bus motor seemed like the obvious place to shed weight without compromising performance. However, selecting a new drive motor turned out to be a much more involved process than we had anticipated. The biggest issue was that the specifications and dynamometer tests were commonly incomplete for the motors within our price range.

Our primary issue with using eSTAB's motor was that the Solectria AC55 weighed 122 kg. We calculated that a lighter motor with similar power characteristics could almost compensate for the added weight of a larger gas engine and generator. However, the initial test runs of 5.6 s and 5.8 s we recorded with eSTAB also needed improvement to meet our initial specification of 75 m in 4 s. After learning more about the tires and the final weight of the car we adjusted this goal to 4.5 s. Shedding 60 kg would have been sufficient, but this seemed unlikely with the addition of a more powerful gas engine and a matched generator. Hence we needed to find a motor that was not only lighter, but also considerably more powerful than the AC55.

Considering only weight and power, there were many interesting options. However, with a restricted budget, only series-wound DC brushed motors seemed feasible. Their advantage is that the heavy and expensive permanent magnets are replaced by wound wire coils that produce magnetic fields. Within the series-wound DC brushed motor class, Advanced DC (ADC) dominates the market in terms of volume and is known to produce reliable motors.

However, we discovered a company called NetGain Technologies that takes ADC motor designs and reinforces the common failure points. In theory, this allows for higher peak ratings and more durable motors. Also, of the manufacturers we talked to, NetGain was most sympathetic to our student status, both in terms of price breaks and interest in our project. Motor prices below include the cost of a suitable controller, which in many cases costs more than the motor itself. UQM and AC propulsion provide superior products, as well as an experimental AC motor produced by Raser that isn't currently available, but worth looking into. They are all extremely expensive and the companies expressed no interest in working with us.

Motor / Spec.	Solectria AC55 (benchmark)	UQM	AC Propulsion	NetGain Warp 9
Type	AC Induction	DC Brushless	AC induction	DC Brushed
Weight (kg) Motor+Controler	136	56	80	72
Power (kW) Peak/Continuous	77/34	75/30	150/50	100/28
Cost ($)	$3,000	~$20,000	$25,000	$4,500

Table 1: Motor comparison chart.

Future Motor Suggestions:

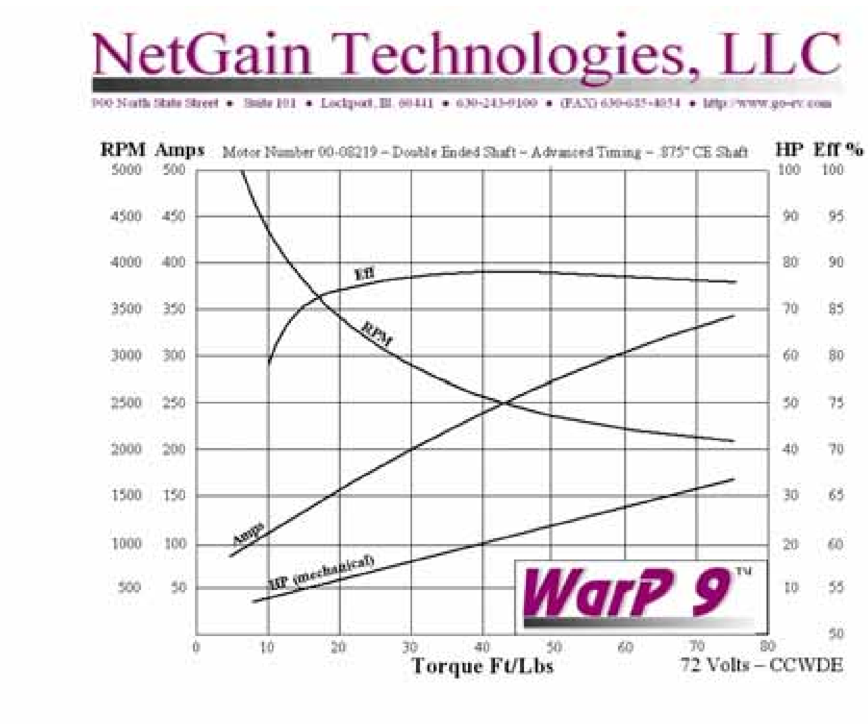
In general, a single large motor is more efficient than two motors of half its size. However, it is possible that the lack of regenerative braking on El-Myra limits the average speed in the endurance event. Unfortunately, it is inefficient to have regenerative braking on the rear wheels, since most (about 60-70%) of the weight of the car is forward during the hard braking. This, in combination with the added complexity and the losses in the system used to recapture the energy, made us decide that we would not try to implement regenerative braking.

Two relatively small motors on the front wheels could implement regenerative braking, and augment power during acceleration. In addition to copies of the popular Etek motor, the two types of motors that are worth looking into are “wheel motors” and “pancake motors”. Both types are still under development by various companies, but both of these types are often small and light. It may be possible to fit them in or near the front wheels of a relatively unmodified SAE car.

Motor Analysis:

By far the largest challenge of choosing an electric motor in the low-cost segment is the lack of good data. The manufacturers of expensive DC brushless and AC motors often provide relatively good torque curves on their websites, but this is generally not the case for powerful, yet cheap brushed DC motors. From what we have been able to gather, the manufacturers of these machines are often small companies that do not possess the equipment needed to test the motor's full range of operation. Another possibility is that they provide cautious estimates to ensure reliable operation.

In the end, we were unable to find a complete set of reliable data for any of the motors that met our specifications. Instead, we attempted to use the limited data that was available and derive a model of the motor. Based on this, we knew that the Netgain Warp 9" we chose, at least in theory, could provide the power we needed to meet our goals. What follows is a short outline of how to derive a model for a series wound DC motor based on limited data, with no guarantee of accuracy. There were errors in the derivation we used in our final report; the following procedure is based on a problem Professor Sullivan assigned in his power electronics course. Netgain provides the chart below for their Warp 9" motor on their website:



http://www.go-ev.com/images/WarP_9_Graph.jpg

The chart only covers 0 to 300 A at 72 V. Based on what we had read about electric drag racers that use this motor and talking to the manufacturer, we believed it could be driven at up to 1000 A, or at 300 V at lower currents. The task is to find out where this would get us.

The basic equations for a series-wound, brushed DC motor are as follows:

$\tau_M = \tau_E - \tau_F(\omega)$ Mechanical torque equals electrical torque minus some torque lost to friction, which is dependent on angular speed. A reasonable simplification is to assume the frictional torque is constant. Electrical torque $\tau_E = ki^{(1+\alpha)}$ is caused by the magnetic field inside the motor. In a permanent magnet machine the current only goes through the armature and the torque is therefore directly proportional to current. In a series-wound system the torque creates the magnetic field of the stator as well and changing the current therefore affects two fields. Torque is therefore proportional to i raised to some power between one and two.

How much current goes through the motor is determined by the voltage across the terminals and the input impedance. The two main components of this impedance are the winding resistance and the variable back-EMF. The latter is a force caused by the armature moving through a field. It is proportional to the angular speed and the strength of the field: $v = ki^{\alpha}\omega + iR_w$.

To obtain a complete model we essentially need to find τ_F, k , Rw and α. This is done in the following way:

1. Look at the current-curve (labeled “Amps”) and write down at least 10 datapoints. Also record the RPMs at the same points.
2. Use a spreadsheet or a mathematical software package to plot torque (the x-axis in the plot provided by Netgain) as function of current. In other words, reverse the coordinates.
3. Most likely this plot will not intercept the Y-axis at zero. For our purposes we will assume that this disparity is due to the frictional torque, τ_F, which we

approximate as a constant. Add τ_F to each value to obtain τ_E, the torque created by the fields inside the motor.

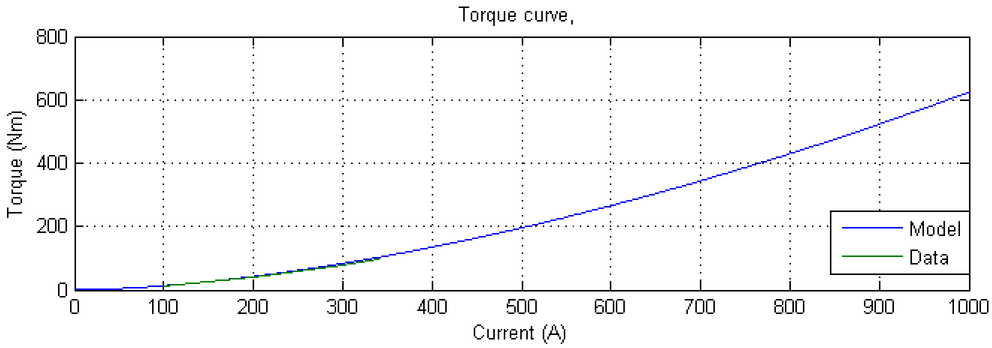
4. Use the software packages to fit a power law to this new curve. Since it passes through the origin it should be of the form $\tau = ci^d$. Looking at our expression for electrical torque, we can see that c corresponds to k in our model, and d = 1+ α
5. The thing that remains to be determined is Rw, and we can find it by using the expression for voltage and setting it equal to 72 V. Then insert the values for k and α that you have derived, and combine them with the numbers for current and angular velocity (in radians). The result will most likely not be a single number, as one may expect, so the best estimate for Rw is probably to take the average.

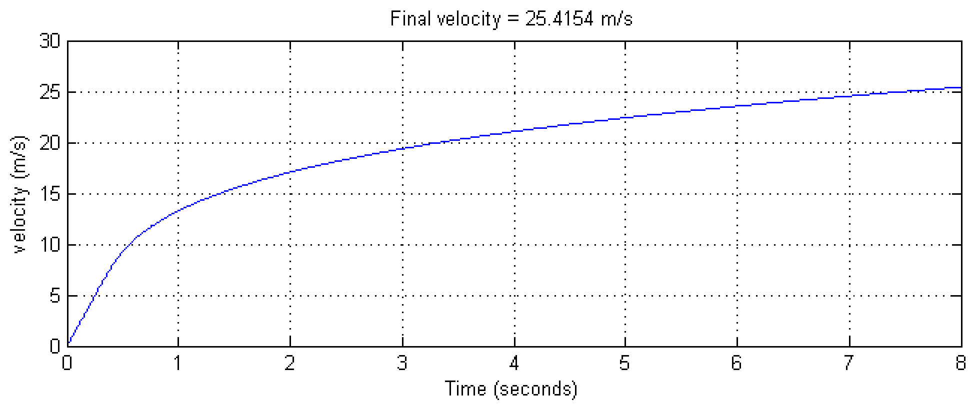
If you already have access to the motor you are considering, you can also run a few amps through it and measure the voltage drop across the terminals. That will probably give you a much better estimate than the last step does.

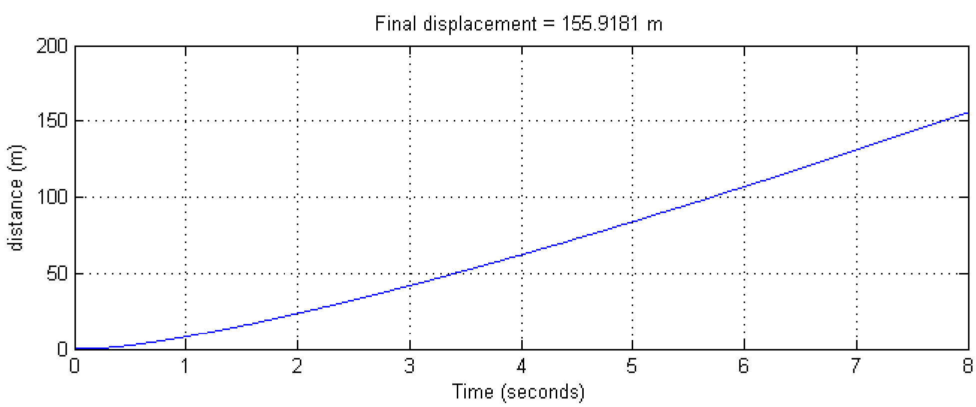
Finally, you should insert numbers into your model and check that it matches the original curves reasonably well. Assuming they do, one can start making predictions about performance. For reference, the values we got for the Netgain motor were τ_F = 2.2 Nm, α = 0.67, k =0.0061 Nm A^-1.67 and Rw = 0.041 Ω.

Assuming a controller that is limited to 1000 A and a car that weighs 460 kg (1015 lbs) the following curves can be computed using the model found in the attached code. It is important to note that model does not try to account for any losses such as friction, slipping, or air resistance. It does, however, model the decrease in energy in the capacitors banks, because the voltage they can supply becomes the limiting factor at high speeds.

Using this model it is also possible to model energy consumption, and model the hybrid as a complete system racing around a track.







Comparing the model to test results

Unfortunately our project has been haunted by reliability issues, as well as rainy weekends. Very little hard data is therefore available, but the two numbers we have from Detroit are 0 - 50 mph in 4.1 seconds and 0 – 57 mph in 5.33 seconds. These two runs do not provide enough data to accurately describe the best El-Myra can possibly do.

However, if we assume that the measurements, which were made by SAE personnel at the track, are accurate then these numbers put a lower bound on the performance of the car.

Time	Measured speed	Predicted speed	Relative error
5.3 s	57 mph = 25 m/s	23 m/s	- 11 %
4.1 s	50 mph = 22 m/s	21 m/s	- 5 %

If these measurements are correct then that means that our model significantly underestimates the capabilities of the Netgain Warp 9" motor. While even 11% is a relatively small error, considering the data that was available, the model does not take any kind of mechanical resistance into account. It is not unreasonable that these exceed 10 % of the total power, which means that our model is off by much more than 11 %.

Hopefully more tests can be conducted to confirm this, but it appears that the motor is not the limiting factor and that our initial goal of 75 m in less than 5 seconds is well within reach, provided the tires can take most of the torque without slipping. This would be somewhat surprising, given that El-Myra ended up weighing an additional 100 kg on top of the 360 kg we expected.

Since our motor has separate terminals for armature and stator windings it can also be used as a separately excited machine. This means that it could potentially be used for regenerative braking, or controlled in a way that allows for less back-EMF and therefore higher speeds. Making these changes to the system would require somewhat complex control mechanisms, but is within the realm of possibility. With minor modifications, the model derived here can also be used to test such a configuration.

Generators

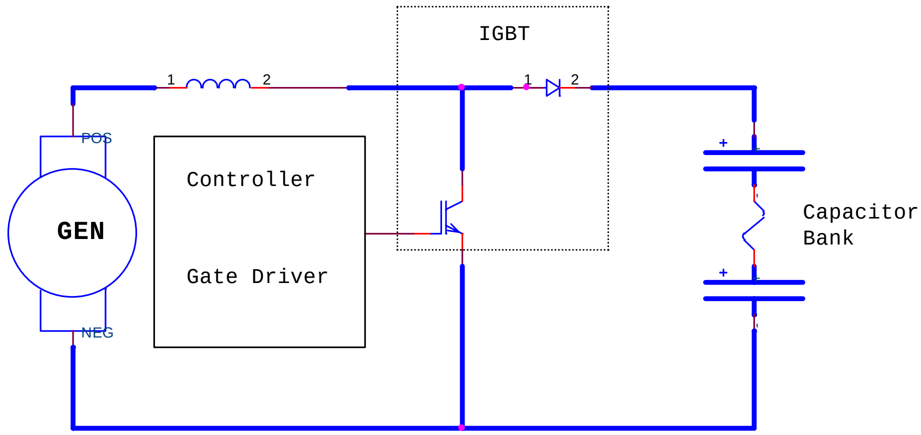
Our systems uses two Etek motors connected in series as generators. They are permanent magnet motors, provided they do not saturate, the voltage constant given by the manufacturer is 72 RPM / V. The plan was therefore to have their shafts driven at approximately 3500 RPM, so that they would output 48 V each. That is what they are rated for, and it would give us 96 V at the input to the DC-DC converter.

One of the reasons we chose this speed was that we were worried the system would overheat. This became an even greater concern after the generators were moved to the bottom of the car where the air flow is comparatively small. However, during testing we discovered that the generators did not even warm up noticeably.

While we do not have any numbers on how much current went through them, the capacitors were charging relatively fast on several occasions. The highest generator voltage we ever measured was 80 V. We have no reason to doubt the constants we have for the motor, and assume that this disparity is either caused by the engine running at lower RPMs than we expected or that the gear ratio is incorrect. Fortunately, our inductor core is larger than it has to be. With a little experimentation it should be possible to compensate for this error by reprogramming the microcontroller in the DC-DC converter.

DC-DC Converter

The power-section of our DC-DC converter is a relatively straightforward implementation of a boost converter using average mode current control. These are well explained in many texts and we will not cover the basic operation in this report. Instead focus on the decisions that make our implementation unique.

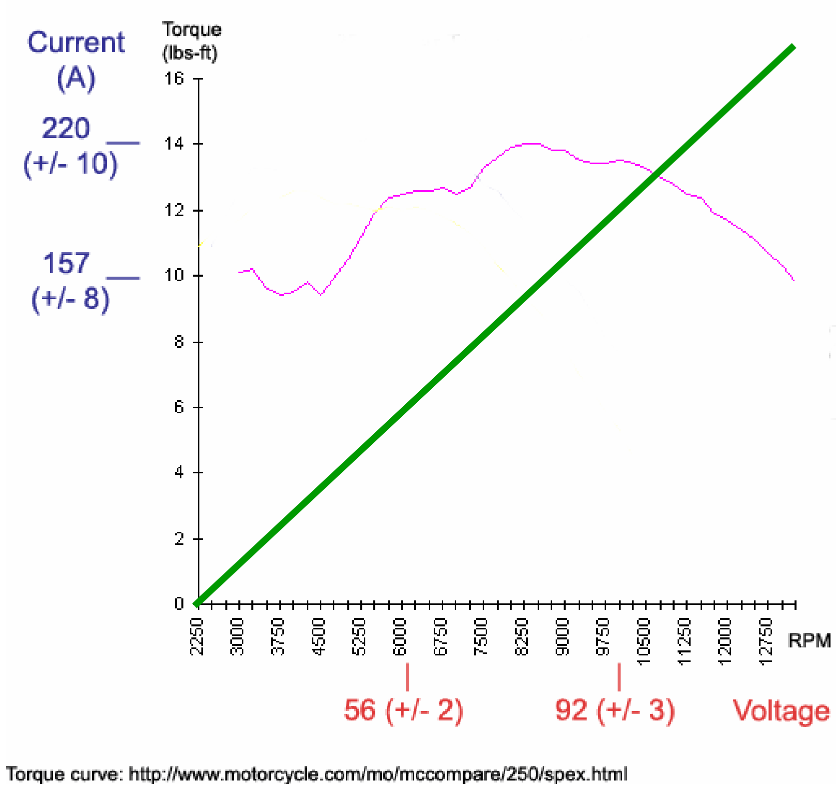


DC-DC boost converter

There are two main differences between our converter and those that are commonly described in textbooks. First of fall, one should not assume that the input voltage is constant or fixed. Overheating may force the engine to run more slowly than you anticipated, or it may just be affected by weather or other factors. In our case, the operating voltage is somewhere between 70 and 75 V, not at the 100 V we planned for.

The other difference is that the output voltage is not steady either. If you use batteries to store energy you can probably fix the output voltage somewhere between 13 and 14 V. However, the voltage of the capacitor banks on El-Myra will vary anywhere from 80 to 270 V (or more) in a single lap. The control system inside the DCDC converter has to somehow continuously compensate for this.

The last thing you must consider is that the DC-DC converter affects the operation of the engine. When using a permanent magnet motor as a generator, the current is approximately proportional to the torque. As explained in the previous section, the input voltage is assumed to be proportional to the rotational speed off the shaft. So if the DC-DC converter draws more current from the generators, it effectively increases the load on the gas engine. If everything else is held constant, this will probably cause the gas engine to slow down. Similarly, if the converter draws less current, the speed will go up unless the throttle controller on the engine compensates for the decreased load. Ideally you want to push the engine so that it operates at the point where it outputs the most power. One possible strategy for making that happen is outlined below.



Motorcycle engine torque curve with control function superimposed

There are three things to notice on this graph. One is the double meaning of each axis. If the motor is outputting 10 lbs-ft, that means the generators are outputting 157 A. Similarly, the RPMs are related to voltage by a constant. The pink curve is the torque produced by a Kawasaki Ninja 250 engine, which should be similar to ours. Note that this is only the maximum torque, if the throttle is only half open a different curve will apply.

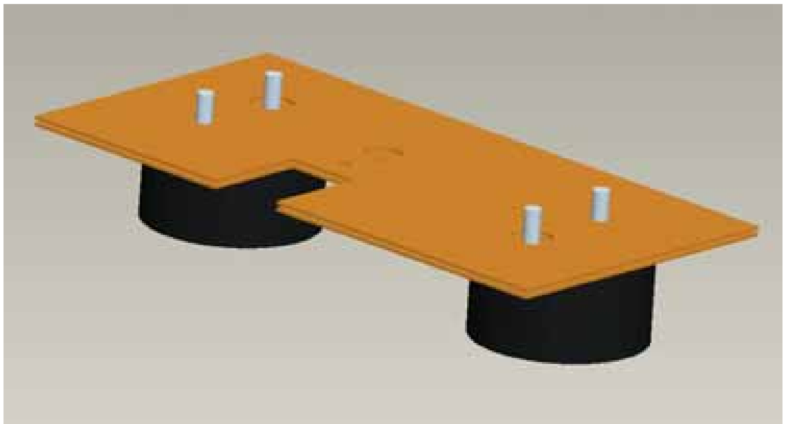
The green line is one possible configuration of our control circuit. The circuit measures the voltage output by the generators. Based on this it decides, either by using a function or a lookup table, what the current going into the capacitors should be. For instance, if the input voltage is 92 V, it will attempt to draw approximately 190 A. If the gas engine cannot deliver this, the speed will drop. In the next iteration the controller will then see a lower voltage and consequently draw less current. If all goes well, the system will end up at equilibrium. If the converter and the engine throttle are controlled separately, it is extremely important that at least one of the control responses is sufficiently damped. Our system oscillated a lot in the beginning, but this seemed to improve somewhat after the engine controller was updated with new firmware.

The other major components of our system are a AMCC-1000 core produced by Metglas. It is wound using 2/0 welding cable and is gapped to only provide approximately 50uH inductance. Calculations done by Jennifer Pollock suggest that the much smaller AMCC-630 would also have been sufficient. However, it would have taken considerable time to acquire a new one, and this was equipment we inherited from eSTAB's original DC-DC converter.

For switching we use an IGBT made by Powerex (1200 V, 400 A) and the gate driver that is designed for it. A custom printed circuit board is available for the latter and we strongly recommend it. These IGBT can do hard switching up to 30 kHz, but our implementation was limited to 25 kHz by the microcontroller.

We built a custom circuit to isolate the high voltage from our 12 V system. After testing the various modules on breadboard in the lab, a copy was assembled on perforated board. The reason we used perforated board, without any conducting surfaces, is that it is a very good insulator. We soldered, rather than wire wrapped, to improve electrical connections and reduce inductance. While this is generally a good solution, the car experiences vibrations that make this a reliability issue. The connectors that are attached to long cables, in particular, show signs of weakness. A custom printed circuit board would have been a much better solution, but at the time we were not able make one ourselves or communicate the design requirements to others.

The most distinct feature of our converter is the copper bus bar and capacitor assembly. The IGBT is located right in the middle, with three terminals for generator input, common ground and the positive output off the capacitors. The last two attach directly to a sandwich of two 1/16 inch copper plates with a 1/32 inch sheet of Lexan in the middle. This leads to the shortest possible conduction path and is designed to minimize stray inductance. The latter is important to avoid voltage spikes during switching and to increase the efficiency of the converter.

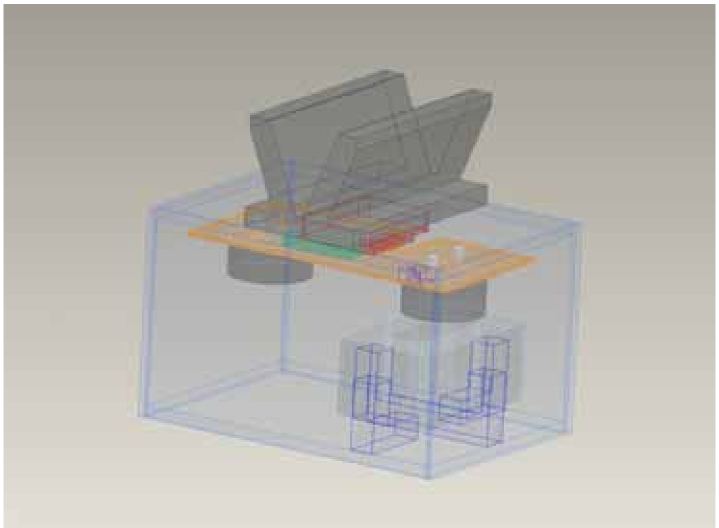


The bus bars and the UL31 capacitors. The IGBT is mounted in the middle with the terminals facing down.

Clearance holes are drilled so that each capacitor post only touches one of the plates.

The original design, with the inductor core (grey) inside the box. It was taken out after we decided to use a standard NEMA box.

The heat sink (black) can clearly be seen, with the IGBT (red) attached directly underneath it. The gate driver for the IGBT is drawn in green.



In addition there is a large 2uF capacitor mounted directly onto the common ground and capacitor output terminal, to further reduce spikes. Two 150uF capacitors smooth the current waveform. The “UL31 unlytic” are special film capacitors, produced by Electronic Concepts that have very low equivalent series resistance and can take high currents at up to 80 kHz. They help reduce the voltage spikes, but also ensure that the ultracapacitors are not exposed to the AC output of the converter. Ultracapacitors are relatively slow and would not respond well if they were charged with pulses at 25 kHz.

Future DC-DC converter work

Analog solutions are commonly used for this kind of application. The IEEE papers we found suggest that it is only in the past ten years that researchers have attempted to use microcontrollers to control DC-DC converters. The reason we still chose to use one was two-fold. After spending almost two semesters working on the analog system, without measurable success, it was necessary to rotate within the team. The composition of our team, and the courses we were taking at the time, made a digital solution appealing. The other argument for using a microcontroller was that it adds a lot of flexibility.

At this point we would not rule out building a control system from scratch, using basic components rather than the chips that promise to do everything for you. Another option, which we only realized later, is to build a "hybrid" analog/digital control circuit. This way one can keep the elegance and precision of an analog solution, and still get the added features that a microcontroller can offer. For example, switching can be controlled by the analog devices, while the microcontroller determines the average current. You can then compensate for deviations from the assumed model by updating the software, rather than replacing resistor values. For example, if the gas engine turns out to provide less torque than you expected, you can simply change a look-up table and adjust the current down to make sure it does not stall.

One of our major regrets is that we did not get around to making a printed circuit board for the control circuitry. Though it has kept together so far, the perforated board we used is not suited for the vibrations that the it will experience on the car.

With regards to the power section of our converter, we are generally quite happy. We originally planned on having the inductor inside the box. Otherwise we would have chosen a smaller design and avoided putting the copper bus bars under the lid. It also turns out that the IGBT does not get as warm as we feared at first. Pending further testing, we wanted to remove the heat sink and instead attach the IGBT to the water cooling that we added for the motor controller.

Ultra capacitors:

Our power pack uses 98 of Maxwell Technologies' Boostcap Ultracapacitors. Each capacitor can charge to 2.7V and has 2600 F of capacitance, bringing the system voltage to 265 V and total energy storage to about 930kJ. Each capacitor weighs only approximately 460 grams (~1 lb), but with the necessary connections and mounting devices the weight almost doubles.

Tests have shown that we could lower car weight by removing energy storage, but we would like to keep the voltage up. We believe that it may be possible to reduce the size and weight of the power pack by using more, but smaller, capacitors. The total voltage would have to go up, since less capacitance means that it will also drop faster once the motor draws current from it.

Batteries are also an option, with Lithium Ion and Nickel Metal Hydride topping the power-to-weight ratios. We believed that batteries were inherently too heavy, but battery technology is rapidly evolving and devices are emerging that bridge the energy density, power density gap.

Capacitor Safety

In the beginning of the project we focused almost exclusively on the electrical risks associated with the capacitors. Though we had some notion of the chemicals involved, we assumed that it was unlikely that we would every have to deal with a damaged capacitor. But that was just what happened. The electrolyte used in the capacitors is an organic solvent know as acetonitrile.

Anyone working on the car should be familiar with the MSDS datasheet information on this chemical. The primary danger is that, in the event that a capacitor is ruptured, the vapors and smoke are highly toxic and possibly lethal. Safety equipment must include insulated cable cutters (to remove high power wires that could be live), proper type fire extinguisher (see MSDS datasheet on Maxwell's website), butyl rubber gloves and a proper respirator (see MSDS datasheet). Discuss safety procedures before going out to the track. Make sure someone is in charge and has a plan in case of an accident.

Capacitor Balancing

Anyone who designs a power pack, which is presumably made up of many cells, needs to consider the possibility that the cells could charge unequally. In our case the capacitor bank is modeled as one giant 265 V, 26.5 F capacitor. In reality it is made up of non-identical cells, which could result in unbalanced charging depending on the charge-discharge characteristics. The most extreme example is that the capacitor bank is charged to 265 V, but that in reality one capacitor is charged to 265 V whereas the other 97 are at 0 V. This cannot happen, because the capacitor would fail long before it reached this voltage, but it illustrates less severe cases in which one or more capacitors are overcharged.

If left unchecked, the capacitors with lower capacitance could charge to more than 2.7 V. The most likely result of this is that the capacitor will break down over time and start behaving like a resistor. Charging could overwork the capacitor and cause heating. In combination with the equivalent series resistance, this can potentially lead to catastrophic failure.

To avoid unequal charging, balancing circuitry should be put in place. Maxwell sells "active balancing circuitry" which it recommends for use in high duty cycle applications. Our system is on the border of what Maxwell defines as "high duty cycle", in terms of how far the capacitors are discharged before they are recharged again. The "active" solution detects the voltage of adjacent cells and sources what is needed to balance the system. We were not convinced that these circuits would actually help in our case, they can at most source 300 mA, a current that is negligible when the DC-DC converter is charging the system at 100 A or more.

The circuits do, however, at least reduce the effects of variations in leakage current. We used a passive solution to balance the capacitors. More specifically, we put high precision 1 W rated resistors in parallel with two and two capacitors in the pack. This provides a consistent leakage path that overwhelms the relatively small (but variable) internal leakage. Future teams should seek to develop a better understanding of balancing issues than we were able to.

Capacitor Boxes

One of the major tasks of the electrical team was to design and construct proper containment boxes for our 98 Maxwell Boostcap Ultra Capacitors. They are all connected in series and power the main drive motor. Since the voltage of capacitors adds in series, the maximum rated voltage of our system is 265 V, at which point it stores approximately 930 kJ. While we sized our capacitor box based on the voltage we wanted (using the largest ultra capacitors we could get), it is possible to further reduce the size and weight of the power pack by considering smaller, and therefore lighter, capacitors.

The important variable here is that the car should be able to complete two successive acceleration 75m acceleration runs, the equivalent of the worst case scenario we would expect to encounter on a track. Any capacity above this is most likely never used. The required energy can be estimated based on the weight of the car and the motor that is used. The latter also determines the minimum voltage at which the system will function, something that must also be taken into account. Maxwell is not the only vendor that sells ultra capacitors and we recommend that you get an overview before choosing a system.

Design and Fabrication

There are three main criteria that the design of the capacitor boxes must fulfill. Rigidity, isolation and chemical containment, due to the dangerous nature of the electrolyte commonly used in ultracapacitors. We chose a modular design, consisting of racks to secure the individual capacitors and a containment box to hold and isolate the racks themselves.

There were several constraints on the design of the capacitor racks. Compactness was key, the capacitor boxes represented the largest component on the car. Another concern was the seal along the top and bottom of each capacitor. This seal prevents the electrolyte, which is vital for the device to function and hazardous at the same time, from leaking out. The risk of rupturing a seal prohibits the use of the capacitor posts as a mounting point. This leaves the can itself as the only option. Maxwell mounts them in heavy aluminum containers. To save weight we used heavy duty zip ties around a rubber ring, cut from a bicycle inner tube, for grip and vibration reduction. While the custom aluminum bus bars that we made provided a good connection between capacitors in the same rack, inter-rack connections should be more flexible to avoid stress concentration on the seal of the connecting capacitors.

Another concern for rack design is galvanic differences between different components in the capacitor circuit, such as the threaded post and the nut. In our case we used stainless steel nuts (close in galvanic series to the aluminum post) and mostly relied on an aluminum impregnated compound that can be applied to the connections to prevent galvanic breakdown. It is especially important to keep this in mind when copper and aluminum are used in the same circuit.

Pro-Engineer (ProE) became a useful tool once we had general drawings of the rack design on paper. On the computer models the dimensions could be displayed easily and precisely. While examining the box in ProE, it became clear that half inch Lexan would be required for the top, bottom, front and back parts of the box with quarter inch Lexan for the two largest sides. Using quarter inch Lexan saved a lot of weight and was deemed sufficient since those sides would not be supporting the capacitors, only providing a physical barrier as well as some rigidity. Part of the idea for modularity of the design was that the racks could be easily accessed and removed. It is highly recommended that the box can be opened in a matter of minutes rather than in an hour or more. The 44 screws on the outsides of each box took nearly 2 hours to take out and replace caused us a lot of trouble throughout the course of the project. Hinges or a latching mechanism could be good alternatives to screwing your hours away.

Three major problems arose during the machining of the box pieces. When the grooves to hold the racks (quarter inch slots) were milled into half inch Lexan, the material warped upward. This is due to the loss of mass on one side paired with the heating from the milling. The problem was lessened by using clamps to pull the top and bottom pieces together while drilling the holes for the face plates of the box. The second problems was that the length and height of the box (29.5”, 13”) strained the capabilities of the Bridgeport mills in the machine shop. If boxes of similar size are made in the future, outsourcing the machining of the parts should be considered. The boxes were completed using elaborate setups involving multiple clamps and the master machinist's wealth of knowledge.

Electrical Safety Considerations

Safe containment of the high power systems of the car is accomplished though three processes: physical isolation, electrical shutdown and providing information to those around the car.

Physical Isolation

When looking at the vehicle, the most apparent isolating components are the Lexan capacitor boxes described above. Lexan is both tough, compared to glass or plexiglass, and transparent. This makes it structurally sound and allows for easy inspection of the capacitors.

The high power cables are mounted to the boxes using angled conduit fittings. This holds them in place and prevents chafing against the Lexan. On the outside they provide an anchor for the crush-resistant conduit that encloses all high power cables.

Another important isolating element is the NEMA rated box enclosing the DC-DC converter. The primary purpose of this component is to keep dust and gravel out of the converter, while providing physical isolation between those around the car and the copper bus bars inside the converter. Although the converter holds little charge in its two 120 microfarad capacitors, the charge on the bus bars is potentially lethal. The box should not be opened while the relay in the converter is closed, and extreme caution exercised when the bus bars are charged.

To connect the high power components we used tough 1/O and 4/O welding cable. The gauge is dictated by the current level in that portion of the system. These cables are isolated using shock resistant conduit that also protects them from the elements or abrasion due to vibrations.

Isolation between the high power drive circuit and low power (12 V at low current) control circuit is essential for safe operation of the system. The low power circuit runs off of a 12 V battery with ground reference of the frame. Since this circuit powers many of the delicate electronics critical to many of the car's subsystems the physical isolation of the high power circuit must be maintained. The critical points, here, are where the low power and high power circuits interface. These points are the DC-DC converter, the relays of the capacitor boxes and motor controller.

The DC-DC converter solves the problem of isolation by using optoisolation chips at each point of contact between the high and the low power circuits. These chips operate by converting input voltage to a certain intensity of light from an internal photo-emitting diode. This light is then detected across a short gap and converted into a proportional output voltage. The important feature here is that there are no conductive connections from one side of the chip to the other. Though the method is not stated explicitly, the motor controller and the controller's hairball interface probably use the same technique to achieve isolation.

Electrical Shutdown

In addition to physical isolation, the second factor that ensures the safety of our system is the ability to contain the high voltage within the capacitor boxes. This can be triggered by the driver, a bystander or the motor controller. In each capacitor bank there is a Kilovac realy capable of interrupting up to 2000 A. In addition, there is a fuse in each box sized so that either one will quickly melt if the current exceeds 1000 A.

The relays are operated using a 12V control line to mechanically make or break the connection between the two main posts. Since the connection is "naturally open", meaning if the control line breaks or is off, then the high power conduction path is broken. 12V must be applied to the control leads to close the relay. To control the Kilovac relays three "big red buttons" are wired in series. If one of them is pushed, all four relays will open. These buttons are mandated by the rules of the competition to provide the driver, or anyone else around the car, with the ability to cut the power.

Energy Storage Information

The information necessary for safe operation of a hybrid car containing any form of mass energy storage comes in two parts: onboard power pack monitoring and knowledge of the chemicals inside the energy cells. In our car, charge information is displayed in two ways. If a bank's voltage exceeds 30 V a red LED will light, indicating caution for those working in and around the car. This circuit (mandated by competition rules) is completely contained in each box so as to preserve physical isolation of the high power system. In addition, there is a multimeter in each box that makes it possible to read the voltage directly, without opening the relays.

Testing the Car

By the end of ENGS 290 only one of the capacitor boxes was fully assembled to validate the design and show that sufficient rigidity was achieved. Over the course of the spring term the boxes were completed and mounted on the car. We ran several successful tests with the car. The current drawn out of the boxes was indirectly limited by defining the max current supplied to the motor to 300 A. No heating or electrical problems were detected, but the acceleration was lacking since the torque produced by the motor is proportional to current.

The first real test of the system came during the Formula Hybrid competition when we raised the current limit on the motor from 400 A to 800 A. After about 2 seconds of amazing, but unmeasured, acceleration one of the capacitors experienced a catastrophic failure. A rough estimate is that the motor was drawing between 300 and 350 A out of the capacitors at this point. The aluminum can melted and released the electrolyte into the box, filling it with smoke almost instantaneously. Afterwards the soot on the Lexan made it very difficult to tell what had actually happened without opening the box. The cause of the failure is yet to be determined.

The capacitor was not one linking two racks together, hence we do not think its seal was exposed to more stress than that of any other capacitor. Since this was the first time we ran the car on high current we suspected that the equivalent series resistance caused the capacitor to heat up and explode. However, we tested all the other capacitors and they all had values well within the specifications. The damaged capacitor was removed in a safe environment and sent back to Maxwell for analysis. We have not been able to obtain any results at the time of this report.

In order to exhibit the car at the Detroit FSAE competition, the capacitor boxes were cleaned and reassembled. The car made it to Detroit and ran several events including an acceleration run, autocross, and passed "tech inspection" by electrical engineers brought by SAE to determine whether it was safe to run the car.

The acceleration times were 0-50 mph in 4.1 seconds and 0-57 mph in 5.33 seconds. These times are good, but we believe that the car is capable of doing even better in spite of the fact that it has mysteriously gained another 100 lbs from somewhere, bringing the total up to 1015 lbs. In Detroit the current out of the capacitors was limited to 350 A. In theory, 450 A can be drawn for short periods of time without the risk of a fuse blowing. This increase could significantly improve the performance of the car, but could not be done before the end of the term because some the palm pilot necessary to program the motor controller was lost in Detroit.

The current status of the car (as of June 7th 2006) is that the electrical system is working and tested close to maximum power. To test the cars full capabilities, the lost equipment needs to be replaced (see Café Electric webpage). The DC-DC converter had an unknown failure in Detroit (stopped charging when the power pack reached generator voltage). We checked the likely points of failure and found no problems with it. However, an unresolved engine problem has prevented further testing.

Tips

1) Don't start a new project by looking at what we did. We made mistakes, it will confuse you. Figure out how you would solve the problem, then compare it with the implementation that is available. We spent way too much time looking at outdated schematics for eSTAB's DCDC converter, without building up any real intuition.
2) Get your budget straight. It will affect every design decision you make.

3) Design so that you can afford at least one replacement and order them right away. We delayed building things because we knew we had to get everything perfect the first time. Having the spares readily available allowed us to experiment and address problems that did not show up on paper.
4) If there is one part of your system that it's impossible to get to without disassembling the whole thing: Assume that you will have to take it out at least five times.
5) Don't do too much ProE if you are dealing with electrical components. There will be things that you can't bend into that shape.
6) Electrical interference is not a myth. Especially not 2 inches away from a cable carrying 200 A.
7) Electronic stuff you build in the lab does not enjoy the ride. Get custom PCB boards made whenever possible. Avoid solder-perforated board implementations. Use epoxy, not a hot glue gun.
8) Leave room for adjustment. The inputs will rarely be exactly what you expected.

Best of luck ☺