ELECTRICAL DESIGNS IN A SERIES PLUG IN HYBRID ELECTRIC VEHICLE

A Design Project Report

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In Partial Fulfillment of the Requirements for the Degree of

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by

Andrew Tomson Gifft

Project Advisor: Professor Bruce Robert Land

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Abstract

Master of Electrical Engineering Program

Cornell University

Design Project Report

Project Title: Electrical Designs In A Series Plug In Hybrid Electric Vehicle

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The goal of Cornell's CU100+MPG Team was to design, build, and test a series hybrid vehicle capable of achieving at least 100 miles per gallon equivalency while meeting Federal Motor Vehicle Safety Standards (FMVSS) and Progressive Insurance Automotive X-Prize (PIAXP) competition requirements. This was an extremely difficult undertaking as our car would have to not only be functional, but durable enough to drive at high speeds through a rough simulated road course, drive a combined distance of hundreds of miles without needing servicing, provide vehicle safety and crashworthiness equal to production cars, while providing passenger comfort and amenities. We also had to design our car to be marketable to today's consumers.

Our electrical systems were monitored and controlled by custom software running on a National Instruments cRIO microcontroller which handled nearly all vehicle functionality. I wrote software for this device that monitors pedal position, commands torque from the drive motor, starts and stops the genset, and monitors battery health and limiting driving when an error occurred.

Most of our vehicle was custom build which meant I had to build two vehicle fuse/relay boxes, run conduit through the car with over 100 distinct wires, design and build a custom instrument cluster, and write custom control systems for the powertrain, batteries, charger and user interface controls.

Our vehicle has driven over two hundred miles as well as passed all PIAXP technical and safety inspections. We made it through the first round of competition and had some difficulty during the second round with our batteries and had to withdraw from competition. An analysis of a likely cause of this failure is given at the end of this report.

This report discusses the design and implementation of the major hardware and software components I designed and built. It is meant to both describe the design process I went through when designing these systems and as a service manual for the car which will hopefully continue to be improved.

Report Approved by
Project Advisor: ____Date: ________________

100+ MPG

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1 Executive Summary

The goal of Cornell's CU100+MPG Team was to design, build, and test a series hybrid vehicle capable of achieving at least 100 miles per gallon equivalency while meeting Federal Motor Vehicle Safety Standards (FMVSS) and Progressive Insurance Automotive X-Prize (PIAXP) competition requirements. This was an extremely difficult undertaking as our car would have to not only be functional, but durable enough to drive at high speeds through a rough simulated road course, drive a combined distance of hundreds of miles without needing servicing, provide vehicle safety and crashworthiness equal to production cars, while providing passenger comfort and amenities. We also had to design our car to be marketable to today's consumers.

Our electrical systems were monitored and controlled by custom software running on a National Instruments cRIO microcontroller which handled nearly all vehicle functionality. I wrote software for this device that monitors pedal position, commands torque from the drive motor, starts and stops the genset, and monitors battery health and limiting driving when an error occurred. This software is tightly integrated in order to ensure all major systems operate efficiently and safely. For example if the battery management system senses a low state of charge it will automatically start the genset. Or, if the batteries are overheating, the motor control software will limit motor power to a "limp home" mode in order to protect the batteries, yet let the car get off the road or track and clear from any danger.

Most of our vehicle was custom build which meant I had to build two vehicle fuse/relay boxes, run conduit through the car with over 100 distinct wires, design and build a custom instrument cluster, and write custom control systems for the powertrain, batteries, charger and user interface controls. Designing the electrical enclosures forced me to not only consider electrical needs, but component placement requirements, or protection from road debris or engine heat. As the vehicle design matured and new PIAXP requirements were given, these boxes and vehicle had to be re-located and redesigned a total of three times between our first driving test and the second round of competition. Every iteration gave me the opportunity to improve my designs by further implementing industry standard practices and demonstrating production readiness.

Our vehicle has driven over two hundred miles as well as passed all PIAXP technical and safety inspections. Video evidence of our vehicle performance and competition results can be found in the *Data and Results Section*. We made it through the first round of competition passing all dynamic safety tests and a placement within the top 10 in our class. We had some difficulty during the second round with our batteries and had to withdraw from competition. For an unknown reason, possibly power supply switching noise, or poor electrical connections, we had contactors internal to the battery packs open sporadically. This resulted in significant damage to battery sensor boards and could be dangerous if the vehicle was under significant load.

This report discusses the design and implementation of the major hardware and software components I designed and built. It is meant to both describe the design process I went through when designing these systems and as a service manual for the car which will hopefully continue to be improved.

2 Design Specifications and System Requirements

PIAXP provided detailed requirements documents which unfortunately are confidential and cannot be reproduced in this report. The last revision was over 70 pages long describing the safety, design, and efficiency requirements for all aspects of the car, from charger isolation, to static stability factor, to tire pressures. I will highlight some of the major requirements and those which gave us considerable difficulty.

All high voltage electronics must be finger-proof, drop-proof, and have sufficient weatherproofing for its location. This requirement forced us to do a full overhaul of all of our electrical enclosures where we added sealed panel mount connectors and cable glands to every enclosure. We also had to run our high voltage wiring underneath the car as no high voltage wiring or components were allowed to be within the passenger compartment.

The high voltage system must be isolated from the vehicle chassis. It must also be equipped with a ground fault detection system that would warn the driver if the resistance between the high voltage system and vehicle chassis was less than 500Ω per volt. This system must be active both during driving and charging. Nearly all of the commercially available GFD circuits had a limit to the leakage capacitance (capacitance between the high voltage components and frame). Our GFD required less than 1µF. This meant we could not use the EMI filter provided by the drive motor manufacturer UQM Technologies (UQM).

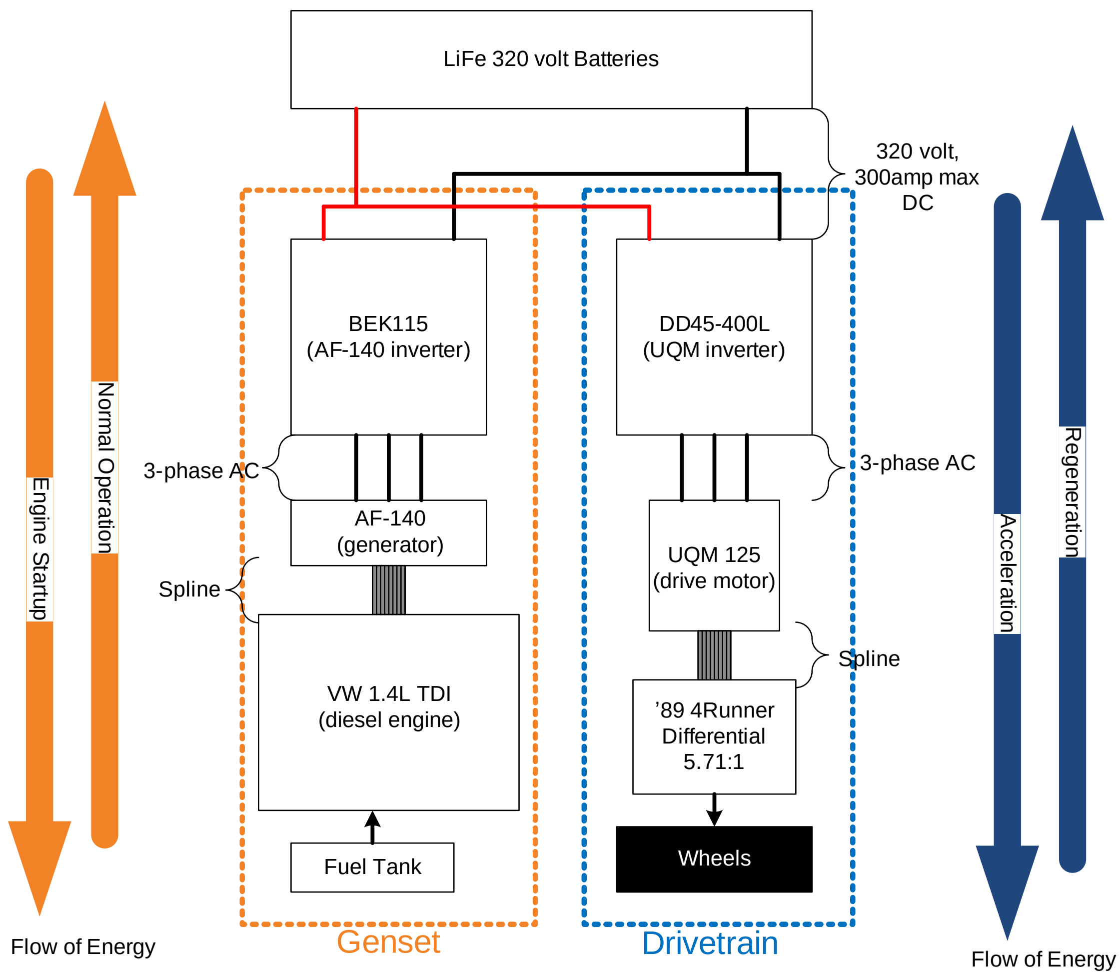
Since we were using lithium iron phosphate batteries, we were required to have a battery management system (BMS) that would monitor the health of the batteries to prevent damage or in the worst case scenario, explosion. We had to monitor cell voltage, currents, temperatures, state of charge, and other parameters and automatically shut down the vehicle or specific components if any of these parameters went out of their safe range.

We were also required to have an intelligent and user friendly charging system that would automatically shut off when the batteries were full or had any errors, as well as maintaining isolation between the high voltage components and the chassis which must be tied to earth ground.

3 Overview of Major Electrical Subsystems

There are two major electrical systems that give our car the required efficiency. First is our high voltage batteries and second is the electrical drivetrain which consists of a engine generator set (genset) and a powerful electric drive motor.

3.1 Electrical Drivetrain



Power Transmission Diagram

The diagram above shows the transmission of power from the fuel tank to the batteries, to the wheels. Our vehicle is using a series-hybrid architecture, meaning the engine only re-charges the batteries and doesn't directly provide power to the wheels.

During charge depleting mode, the genset is disabled, therefore the only source of energy is the LiFe batteries which the DD45 inverter converts to the 3-phase AC used to drive the UQM 125. This in turn drives the differential which spins the wheels. During charge sustaining mode, the drivetrain behaves in the same way, but this time the genset is operational. Besides the brief time the AF-140 spins the engine to get it started, the VW is being loaded down by the generator which converts the mechanical energy from the engine to electrical through the BEK115. The electrical energy is supplied to the drivetrain and LiFe batter pack. The genset is always run at 1700rpm and 130Nm of torque regardless of driving intensity as this is our diesel engine's most efficient operating point. Currently, we plan to turn the genset on when we reach 20% State of Charge (SOC) and turn it off at 85% SOC. As our vehicle nears completion these numbers will likely change with testing, and we will implement different driving modes, such as city, highway, etc which will optimize the duty cycle and SOC limits of the genset.

3.2 High Voltage Batteries and Provided BMS

Our Batteries were provided by Chang's Ascending Enterprise CO., LTD and include various monitoring boards that allow us to monitor the State of Charge, State of Health, and various parameters needed to ensure the vehicle operates safely and efficiently. In order to use the data provided by the batteries I had to understand the architecture and data communicated by each board. This was even more necessary as we had many communication and other errors which we suspected wree spurious. Therefore I had to dig into the functionality of the provided monitoring in order to better understand the source of these errors.

The Batteries are broken up into three different categories: controller's internal to each pack, a "master" controller, and BMS software on our NI cRIO which handles controls for all major systems including batteries, traction motor, genset, and user interface controls.

3.2.1 Internal Pack Sensors / Control

Within each battery pack we have three different boards: one "slave" control board, one SOC board, and two over-charge, over-discharge boards. In addition there are cell balancing controls that operate independently of the BMS system. The diagram below shows a simplified schematic of the boards' power and data lines. Note that dashed lines are opto-isolated communication busses.

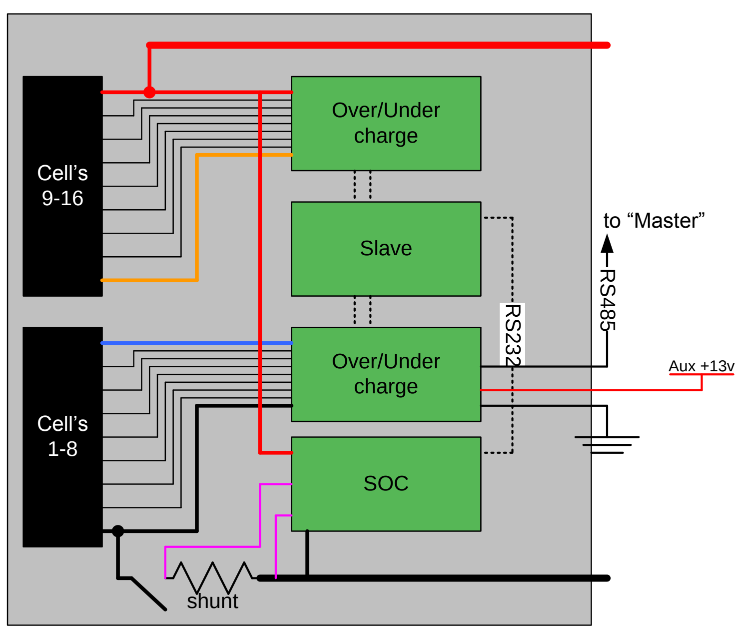


Diagram of Internal BMS sensor/control boards

3.2.2 SOC Board

The SOC board is powered by the ~50 volt array of LiFe cells. It communicates three significant data:

- State of Charge (0-100% in 0.1%)
- Overall Pack Voltage (in 0.1volts)
- Instantaneous current (in 0.1amps)

This data is sent through an opto-isolated RS232 communication channel and is sent to the Slave board. The data is refreshed on roughly 2 second intervals and does not need to be requested by the slave (data is sent regardless of whether slave is working correctly, or powered on). SOC is calculated using an integrator across the shunt resistor, which is also used for reporting current. Note that power to the SOC board is disconnected when the internal Kilovac Contactor is open. This is used to verify that the contactor is open, and reduce parasitic loads on the batteries.

3.2.3 Overcharge / Over-discharge Board

These boards monitor the voltage across each cell. Each board can read up to eight cells. If any of the cells being monitored by the board is over 4 volts, or under 3 volts the corresponding signal is sent. The interface between the Over/Under charge boards and the slave are two opto-isolated digital signals. They operate as follows:

- Overcharge (True = closed, False = open)
- Over-discharge (True = closed, False = open)

The slave board does not know which of the eight cells are over or under voltage. These boards are constantly powered by the LiFe cells and does not need a data request to update the slave. The outputs are updated near-instantaneously.

3.2.4 Slave Board

The slave board is the brain of each battery pack. It receives all data from all sensors and is the only board that communicates outside the battery pack. It is powered by our auxiliary 13 volt battery, and is grounded in common with the vehicle chassis. In addition to receiving the signals from the SOC and over/under charge boards, the Slave also gets temperature data from two digital thermistors placed on the anode or cathode of selected cells. This board also operates the two battery pack fans as well as the internal Kilovac contactor.

The slave board communicates to the master on an RS485 communication bus. The following information is sent by each slave:

- Pack Voltage (in 0.01 volts)
- State of charge(in 0.01%)
- Current (in 0.1A)
- Temperature 1, Temperature 2 (in 0.01°C)
- Overcharge / Over discharge (only 1 bit each, True / False)
- Fan Status (on = True, off = False)
- Contactor Status (closed = True, open = False)
- SOC communication functional? (working = True, error = False)

3.2.5 Master Controller

The master controller initiates all communication with the slave boards. It communicates via the RS485 bus. It periodically poles the slave boards refreshing the information. The master stores the last value of all slave data. Therefore if a slave board loses power, the last valid data sent would be stored and that would be the assumed state of that pack (although the master would detect a communication error). The master board compiles the data from the slaves and sends it to the cRIO when requested. For details on the messages sent see the appendix on Battery CAN messages.

A summary of the data sent to the cRIO is given below:

- Total Voltage (0.1volt accuracy ex: 321.1v)
- Maximum Current (0.1A accuracy ex: 45.4 amps)
- Max, Min, Average Temperature (0.1°C accuracy ex: 20.4°C)
- Fan status (on/off for each of the six packs)
- Relay status (open/closed for each of the six packs)
- Max, Min SOC (1% accuracy), Average SOC (0.1% accuracy)
- Error conditions (over/under charge, communication error, etc. see CAN appendix)
- Battery status (On/Off/Charging)

Additionally new messages were added that provide the following information:

- Pack Voltage for each of the 6 battery packs (in 0.01V)
- Pack Currents for each of the 6 battery packs (in 0.1A)
- Pack Temperature (2 per pack) for each of the 6 battery packs (in 0.01 deg C)
- Pack SOC in 0.01% for each of the 6 battery packs

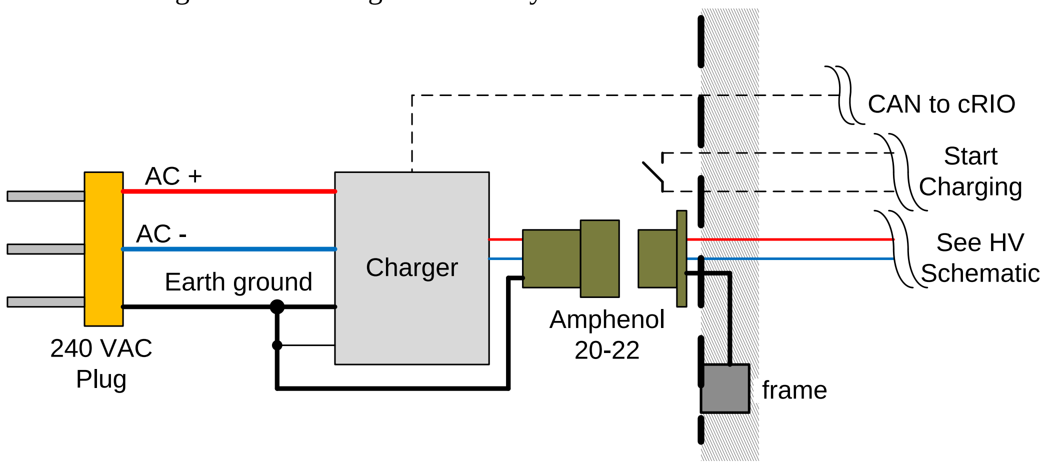
These additional messages are used to diagnose battery problems while in operation. They were added because we had significant difficulty with the electronics within the battery packs and had wanted to be able to isolate which packs were sending erroneous data without having to remove the packs from the vehicle and test them individually. You will notice that the original messages mostly reported, maximum, minimum and average of the appropriate values. We experienced that at times none of these values would be reliable as some boards would be stuck near the maximum, some at zero and giving an average that would be heavily affected by the number of boards stuck at these extremes which was unknown. By isolating the different packs we are able to find what data is reliable and what is not.

3.3 High Voltage Battery Charger

We use a 7kW external charger capable of fully charging our batteries within 3 hours. It is powered by a 240 volt, split phase 30 amp wall outlet and can provide DC power up to 392 volts and limited 18 amps. The charger communicates with the car via CAN and we set the maximum current and voltage limits. The charger reports applied voltage and current as well as errors such as over temperature, voltage etc.

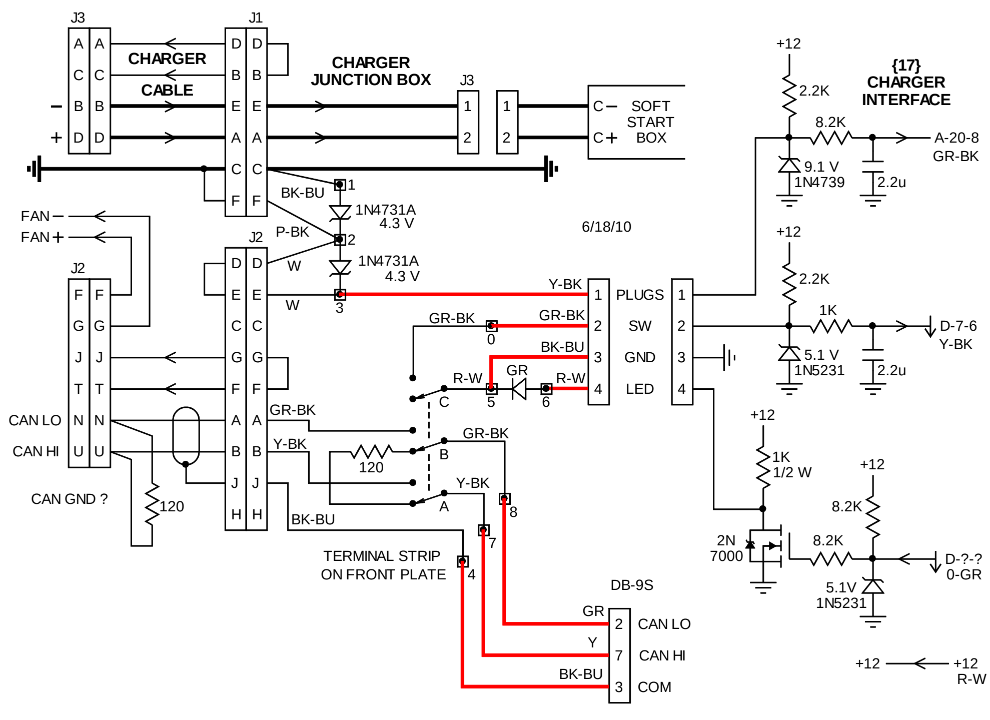
Because of the CAN interface, our charger is controlled by the cRIO which also monitors the battery health. We adopted a fairly simple charging strategy where we would charge at full power as long as all packs remain below 100% and there are no over voltage errors. Once any of these conditions are met the charger is shut down until the error is cleared. This may shut down the charger prematurely as not all packs will be fully charged or properly balanced, but it does protect the cells from being over charged. Once it reaches this state, if further charging is desired it can be performed using alternative software run from a laptop (not built into the car).

A high level circuit diagram of the charger and battery interface is shown below.

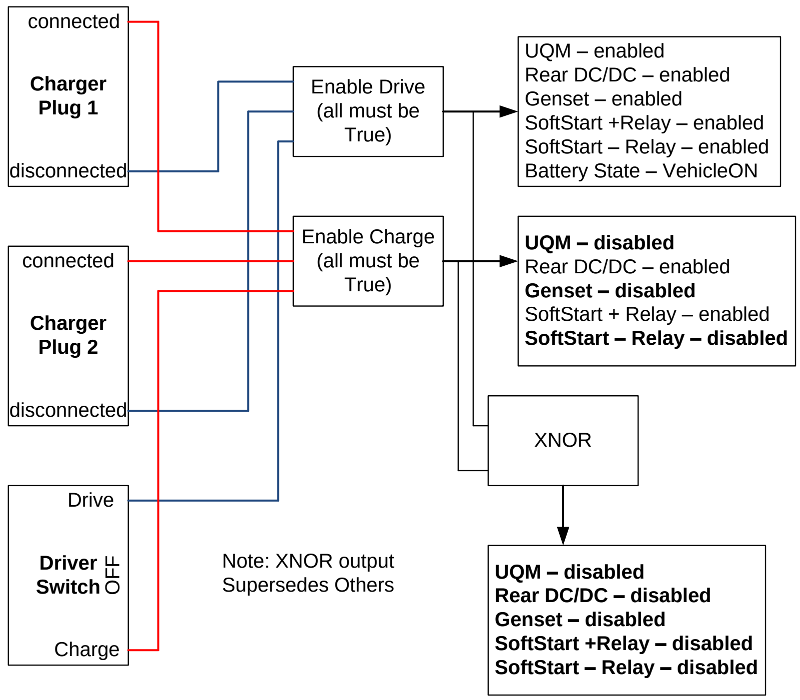


High Level Schematic of Charger Circuit

Per PIAXP requirements, earth ground must be passed through the same connector as the DC-power and immediately grounded to the frame. In order to ensure vehicle cannot drive away with the charger plugged in, there is a circuit of two zener diodes which is held at 8.6 volts when none of the two charger plugs are inserted, if one plug is in, the voltage is dropped to 4.3 volts, and when both plugs are in, the voltage is dropped to 0 volts. The cRIO reads this voltage and disables drive if one or more plugs are inserted and enables the charger when both plugs are inserted. This way we cannot accidentally drive away when the charger is plugged in, risking damage to the high voltage system. A full schematic of the charger, vehicle interface is shown directly below with a logic diagram of what systems are enabled and disabled under the charger switch and plug insertion status.

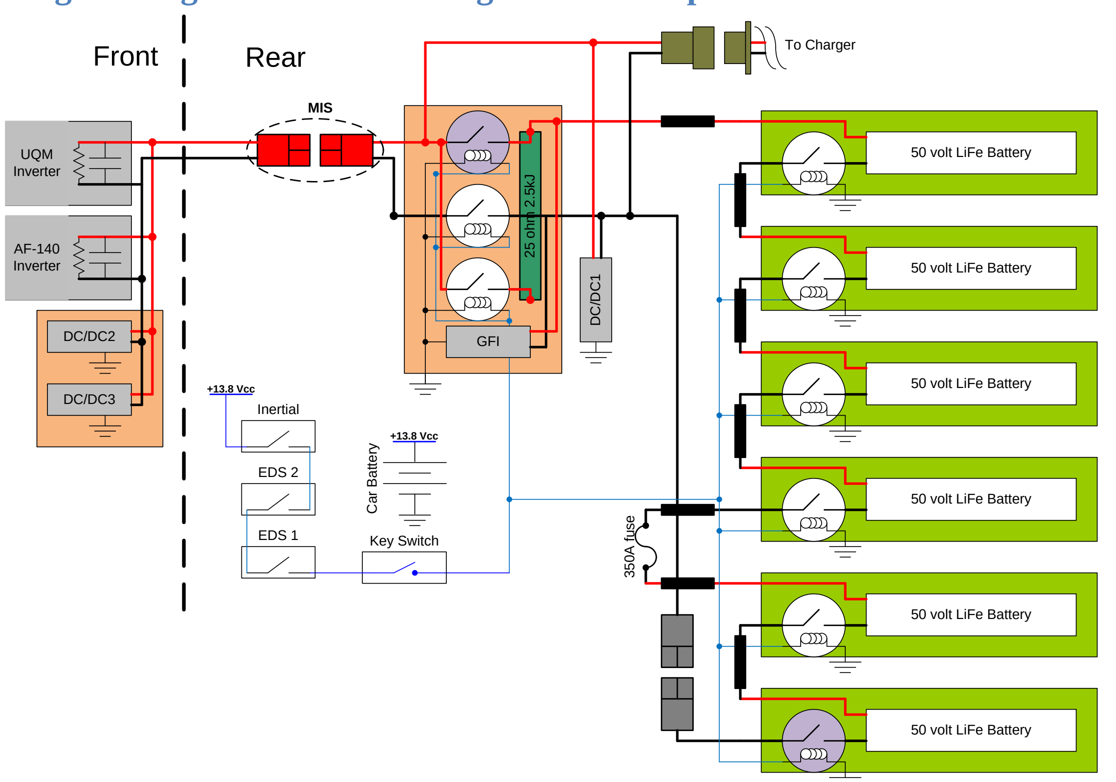


Charger Interface and Control Schematic

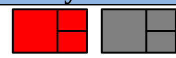
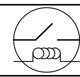
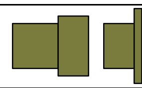


Vehicle Operations Enabled Under Charger Status

3.4 High Voltage Schematic and Significant Components



Symbol Description / Parts List:

Manufacturer	Part Number	Symbol	Description
Anderson Power Products	SB350		Manual disconnect Switch
Kilovac	EV250		Contactors used for Soft high voltage, high power connections, including EDS
Anderson Power Products	SB175		Connector used between Battery Packs
Amphenol	20-22		HV Charger Connector

Continued Parts List

Manufacturer	Part Number	Label	Description
UQM	DD45-400L	UQM Inverter	125kW
EVO electric	BEK 115	AF-140 Inverter	115amp, 3-phase inverter
Lambda TDK	PAF600F280-12	DC/DC1,2,3	300volts to 12volt converter, 600watt max
Bender	IR155-2	GFI	Ground fault detector, analog output
Bussmann	FWH-350A	350A fuse	High power fuse

Motor Inverters

Both inverters have significant capacitance between the +/- high voltage power lines. The UQM inverter has 8,000uF while the exact AF-140 capacitance is unknown, it is between 5,000-10,000uF. There are very minimal bleed resistors on the AF-140 and UQM inverters between 7-10kΩ.

High Voltage Contactors / EDS

The two contactors shaded in purple are the contactors used to meet the EDS specification. Both of these are very close to the corresponding battery terminals, the negative contactor is within the battery enclosure itself. Note that when the EDS button is hit, not only do the shaded contactors open but all high voltage contactors including the contactors internal to the six battery packs. This adds added safety to system as this changes the battery from one 300 volt packs, to six 50 volts batteries, at the voltage boundary from high voltage to low voltage systems.

Notes on schematic

Note that the schematic ignores low voltage control boards. For example the contactors in the orange shaded box are not all connected when low voltage is applied, instead the cRIO closes the negative and soft start relay first, verifies the inverter capacitors are up to voltage, and then closes the main positive contactor. Similar is true for the contactors in the battery enclosures. But the only power source to these contactors passes through the EDS buttons and "key" switch, therefore if one of these switches is open, regardless of the state of the control boards, the contactors must open.

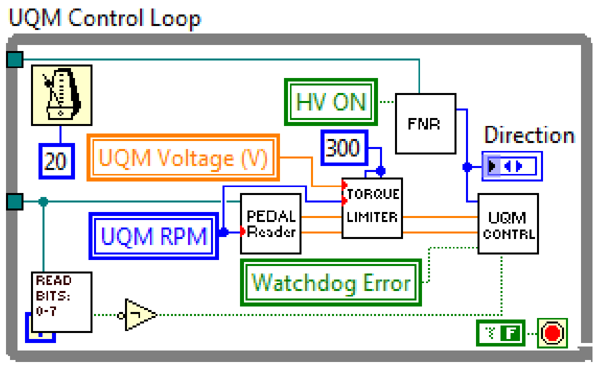
We can also see that there are no high voltage components, or breaks in the high voltage wiring in the middle, or passenger compartment of the car.

4 Vehicle Software

Our vehicle is controlled by a National Instruments compact Reconfigurable Input/Output device (cRIO). This microcontroller allows us to add various IO modules including a CAN module, 16-bit 32 channel analog to digital converter, a 32 channel digital input / output module, and a 16-bit -10 to 10 volt analog output module. These modules are controlled by the LabVIEW software written on the cRIO. This software is very versatile and has allowed us to implement complex controls and difficult protocols very quickly.

Although all software is contained on the cRIO I have selected to discuss the software that controls the powertrain and user interface.

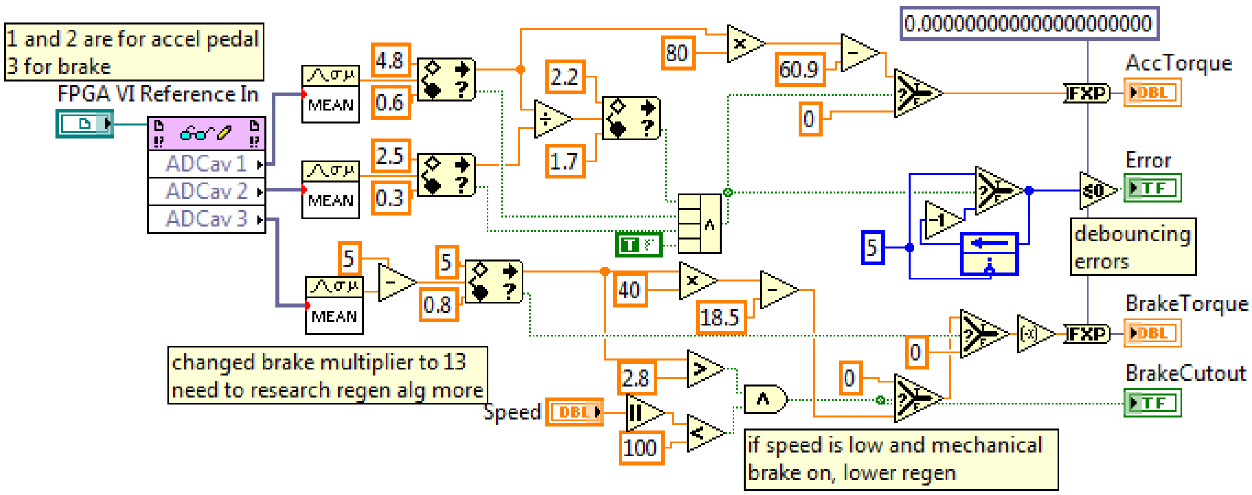
4.1 Drive Control Strategy



The diagram above shows the top level LabVIEW code that reads the brake, accelerator pedal positions, and forward-neutral-reverse switch position as well as giving an option to limit generator current for any future reason, such as additional temperatures monitored, or more advanced control strategies. The blue [300] wired twice in to the "torque limiter" block sets the regenerative break current limit and acceleration torque limit at 300 amps.

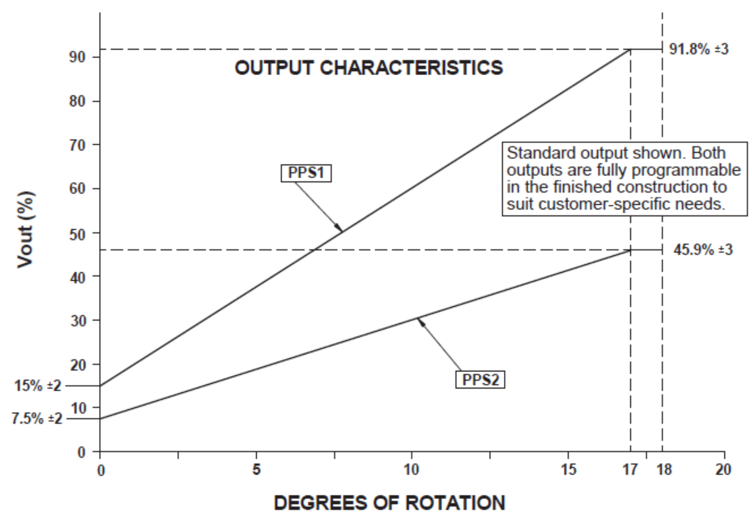
The "FNR" block converts the analog input from the FNR switch to a enum (special type of integer) signifying the desired direction of travel. The "Read Bits:0-7" block gives the value of the first byte of the cRIO digital inputs. The specific input selected corresponds to the switch enabling the UQM regeneration. The remaining blocks are highlighted below.

4.1.1 Pedal to torque conversion



LabVIEW Code for Pedal to Torque Conversion

The block above is responsible for reading the analog inputs from the brake and accelerator pedal and converting them to a torque request. The voltage output characteristics of the pedal are shown below:

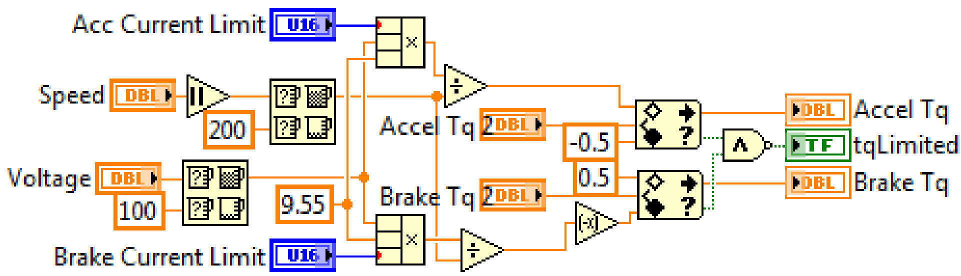


Accelerator Pedal Voltage Outputs

This pedal provides a high level of safety which is used to prevent erroneous propulsion. As the diagram shows, there are two analog outputs which maintain a voltage ratio of 2 throughout the pedal range. They also never reach either voltage extreme (staying within 7.5% and 91.8% of the supply voltage). Therefore if either of the two voltages goes out of range, the UQM acceleration torque is zeroed. Also if the ratio between the two voltages differs greatly from 2.0 the acceleration torque is also zeroed. This protects against cables being disconnected as well as erroneous or noisy signals causing undesirable behavior.

There is a single string potentiometer for the brake pedal which requires inversion (when the pedal voltage is 5 volts, the desired regenerative torque is zero). Therefore I simply subtract the pedal voltage from 5 to get a function linear with the desired torque. Note that the safety controls are not present for braking as it is much safer to have the system over-break than over accelerate. Also because we had to use an existing brake pedal that tied in with the brake master cylinder the potentiometer does not have definite voltage bounds. During testing we experienced some undesired behavior from the UQM when braking at very low speeds. This is likely a result of the rotor position sensor resolution. As the car slowed near stopping the UQM would "jerk" applying braking torque then releasing, then re-applying torque. In order to have deceleration to a stop smoother I added a function that reads the motor torque and disables regen if the vehicle is moving slowly and the pedal is depressed far enough for the mechanical brakes to be activated. This successfully eliminated the jerking behavior.

4.1.2 Current torque limiting



Torque Limiting LabVIEW Code

This software reduces the available drive torque in order to enforce the current limit for both acceleration and breaking. It uses the formula:

$$W = 2\pi(Hz)(Nm)$$

More appropriately for our needs:

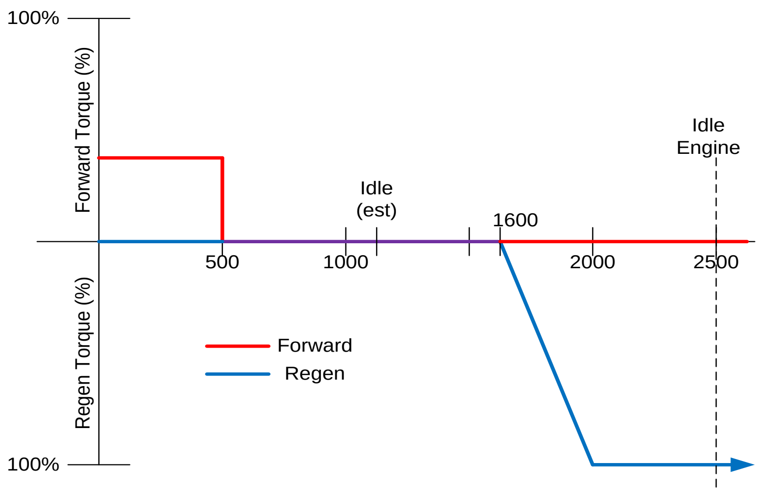
$$Nm = \frac{(V)(A)(60)}{2\pi(rpm)} = \frac{(V)(A)}{(rpm)} \cdot 9.55$$

In order to ensure we have a nonzero and defined current limit I set a minimum voltage of 100 and a minimum speed of 200rpm.

4.2 Genset Startup / Automated Control Strategy

The chart below shows the torque limits on the EVO controller. The non-zero forward torque region is for starting the engine, once it reaches above 500rpm no forward torque can be applied. Around the idle region no forward or regen torque can be applied allowing the engine to idle without a load. The regen torque will increase from 0-100% load from 1700-2100rpm respectively. It remains at its max torque above 2000rpm.

As a safety feature, once the engine reaches 3700rpm, the engine is disabled by the cRIO by opening the relay providing +12 to the engine harness. Simultaneously the EVO motor torque is zeroed to allow the engine to coast down at a normal speed.



Torque Limits for Generator

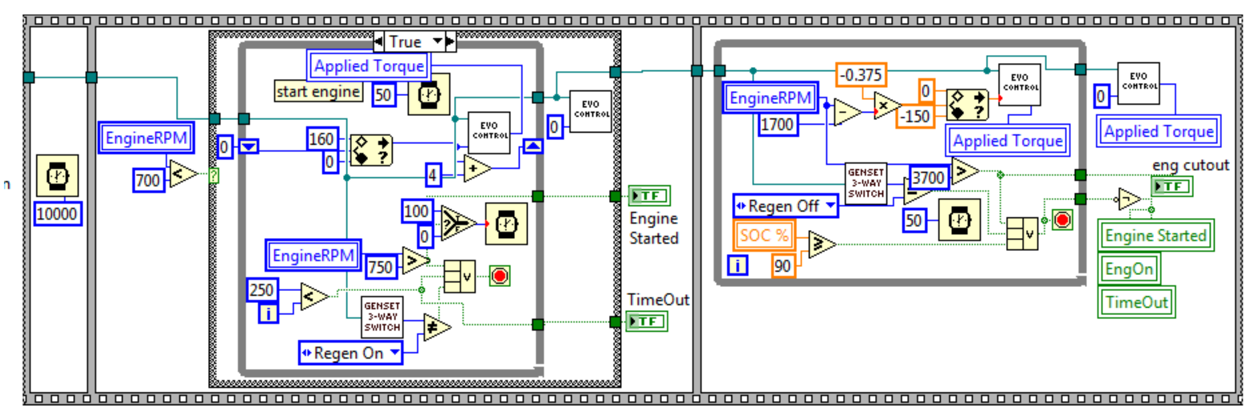
(note: the rpms have changed slightly from the diagram above, but the principle remains the same)

The complex software below controls the startup and regeneration of the generator. This code only runs when the genset switch is enabled and the state of charge is low or the genset is forced on via the switch panel in Section 4.5. The first code executed is a ten second delay. This is to allow sufficient time of the dashboard "Engine Started" led to flash, notifying the driver before the engine is violently started (See Section 4.42). Next the generator torque is increased by 4 Nm every 50 milliseconds up to a maximum of 160 Nm. During the loop can be exited before the full torque is reached if the engine rpm is above 750 rpm or the genset is disabled by the driver. The genset will apply forward torque for a maximum of 12.5 seconds to protect against a stalled engine (it may damage the inverter if high torque is applied to a stalled rotor for a long period of time).

If the engine does start, the second loop monitors engine speed and applies torque following the formula:

$$Tq = -0.375 \times (rpm - 1700)$$

With torque held between 0 and 150Nm. Therefore if the engine speed is less than 1700 rpm the formula results in a positive torque that is held to 0 Nm. Once the speed becomes greater than 1700 rpm the torque becomes negative and is applied up to 2100 rpm when it is maintained at its maximum torque.



Genset Control Software

This loop will exit under one of three conditions. First, if the engine rpm exceeds 3700 rpm. Second, if the battery state of charge exceeds 90%, and third if the genset is disabled by the driver. Under all conditions the generator torque is zeroed and the power to the relay powering the engine harness is opened. This ensures the engine is able to coast down at normal speed.

We experienced intermittent behavior with the genset and did not have time to thoroughly test the system under many situations. Therefore, care was taken to make sure that the genset could always be disabled by the driver via the switch panel in case of engine runaway, excessive heating of electronics, or other malfunctions.

4.3 High Level Battery Management System

The cRIO is responsible for making all battery control decisions all previously described systems are only used for data collection, not processing (with the exception of automatic fan on if temperature >17°C). This setup is ideal as the cRIO has control over the battery as well as the various high voltage loads. The cRIO controls the traction motor (UQM 125) and charger through CAN and controls the generator (EVO Electric AF-140) through analog signaling.

4.3.1 cRIO thermal management of ESS

Note that the chemistry of the batteries being used is such that there is no explosive, or thermal runaway danger, but high temperatures will cause irreversible damage to the batteries and reduce their capacity and lifetime. Temperature will stop rising if all loads are disconnected. Each battery contains two digital thermistors that are placed on the anode and cathode of selected cells. These temperatures are read and updated every 2-3 seconds.

The table below summarizes the actions taken at the various temperature thresholds. Note that all actions taken for lesser temperatures are maintained at the higher temps (for example at 50°C the pack fans remain on)

Temperature (°C)	**Action Taken**
50	If charging, set charge current to 0 if driving, limit regen power to 1C (15kW) limit traction motor to 80kW if SOC>30% disable genset
60	Disable regen Limit traction motor to limp home mode (25kW) If SOC>20% disable genset
65	Disable traction motor and genset Disable all HV loads (DC/DC, AC compressor)

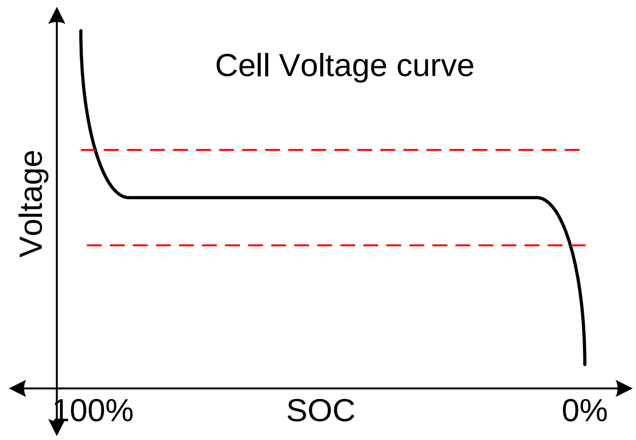
Table of temperature thresholds and actions

4.3.2 Testing plan for Thermal Management Controls

As the actions taken are for the highest temperature of the 12 sensors, we will test our thermal management system by moving one temperature sensor external to one of the battery packs and heating it independently (either with our fingers or a heat gun). In order to test all actions we will drive the car on a dynamometer while the temperature probe is being heated. We will first perform the test at a high state of charge, and then repeat at a state of charge beginning around 25%, and make sure the genset is triggered before heating. This way we can verify that the genset is turned off at the appropriate time, regen is limited (we check by braking hard and reading the instantaneous regen power), and driving power is limited. Of course we will also be watching and listening for the user visual and audio indicators.

4.3.3 Over / Under Voltage Control

The overall pack voltage is continually monitored, especially when the SOC is near the extremes. As with most lithium battery cells, ours have a very flat voltage during most of the SOC range. A qualitative graph of cell voltage vs SOC is shown below:



Qualitative Lithium Ion

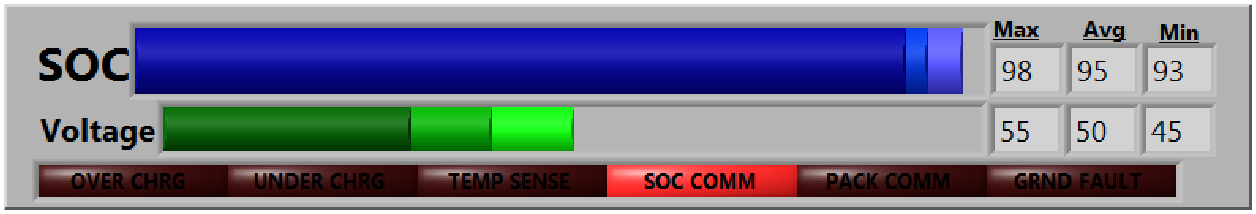
Therefore within the normal operating SOC range we should see very little voltage change. Before we will allow the vehicle to be turned on (High Voltage contactors close) the SOC must be greater than 10% and the voltage must be between 340 and 260 volts.

4.4 User Interface

All vehicle information is given to the driver through a NI TPC-2512 touchscreen computer. This screen is mounted behind and above the steering wheel in roughly the standard position for an vehicles instrument cluster. I designed and coded multiple screens two of which are for normal driving and four for debugging or offering more detailed information but in a format too distracting for the driver to understand while the vehicle is under way. The screens were designed to be selected before the vehicle is underway and then not changed during the entirety of the event. Therefore the information displayed on each tab was selected so the driver would not have to take his hands off the wheel to change screens in order to get necessary information. The last four screens, with detailed information, were meant to be used by the pit crew in the event a problem arises and quick debugging is needed.

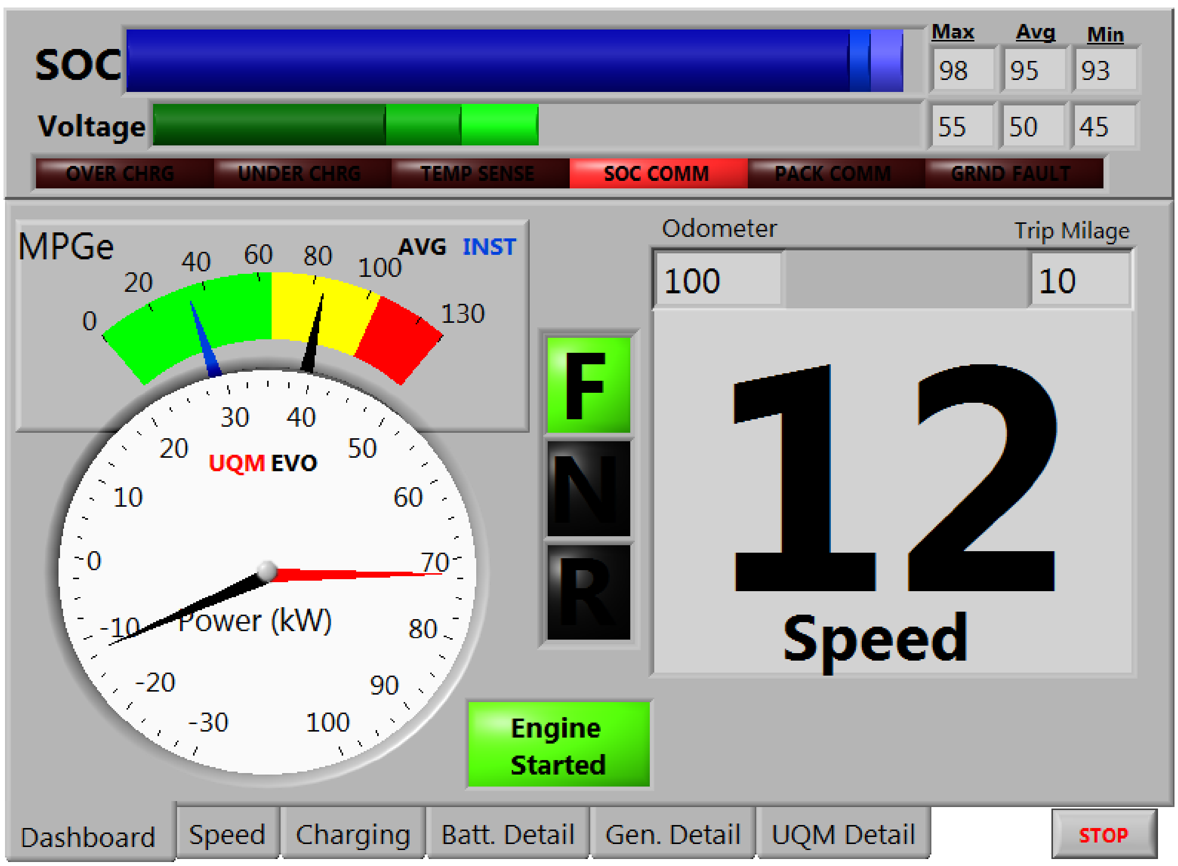
Please note that the data displayed in the following screenshots are not necessarily valid data but are given to show the layout and functionality of the different displays.

4.4.1 Battery Summary Display



Each Tab has important battery information displayed at the top. We have had considerable difficulty with monitoring battery health and performance throughout testing and competition. With the implementation of the new battery messages, we are able to monitor each pack's status. This bar gives the two most important parameters for judging remaining capacity, SOC and Pack Voltage as well as the list of battery errors. Instead of displaying all six SOC's and Voltages I give the maximum, average and minimum so that the driver can see if the packs are extremely unbalanced and drive accordingly.

4.4.2 Dashboard Tab: Generic or emissions sensitive driving



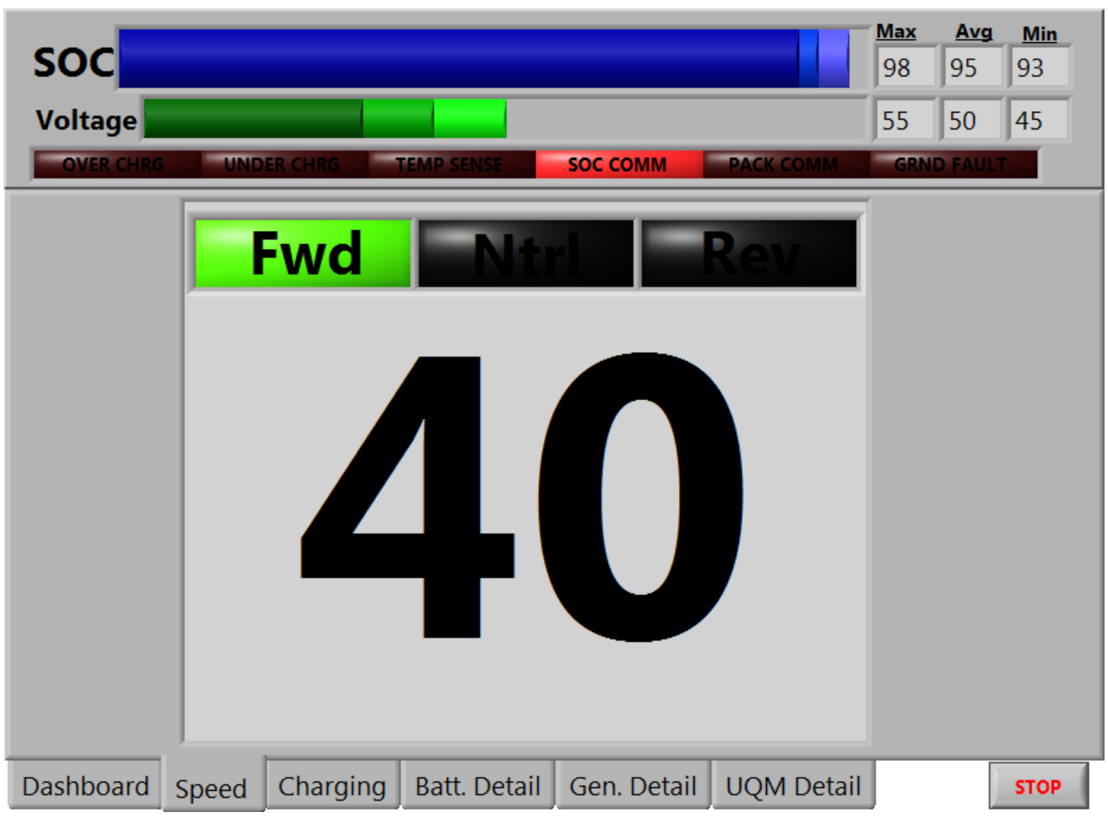
The "Dashboard" tab is designed to be used while the vehicle is under-way. It displays the speed in very large font in order to allow the drive to read the speed with a quick glance. We decided to change from an analog speedometer to digital after the first round of competition. We noticed that the LabVIEW dial's needle is very thin and harder to read. This difficulty is compounded by glare when the sun is shining through the windshield. The driver and I found that the black on light grey text combined with a very large size is sufficiently easy to read even with glare. We also determined that giving a more accurate speed to within a tenth of a mile per hour is too distracting as the decimal changes to quickly to be useful and only acts to distract the driver.

I decided to leave the drivetrain power meter as a needle display as the driver only needs a ball-park idea of the motor and gensets' power (unlike speed which we must maintain very accurately during competition). The driver can also ignore this information without risking damage to the vehicle or violate any axp rules. Above the instantaneous power display, I give the average and instantaneous electric miles per gallon for the current trip. For further information on how this data is generated see the section *Telemetry Data Parser*.

Above the speed I give the expected trip distance and odometer which are useful for the driver to understand how far he has driven as well as being required by FMVSS. The drivers' selected direction of travel is also displayed prominently in the middle of the screen.

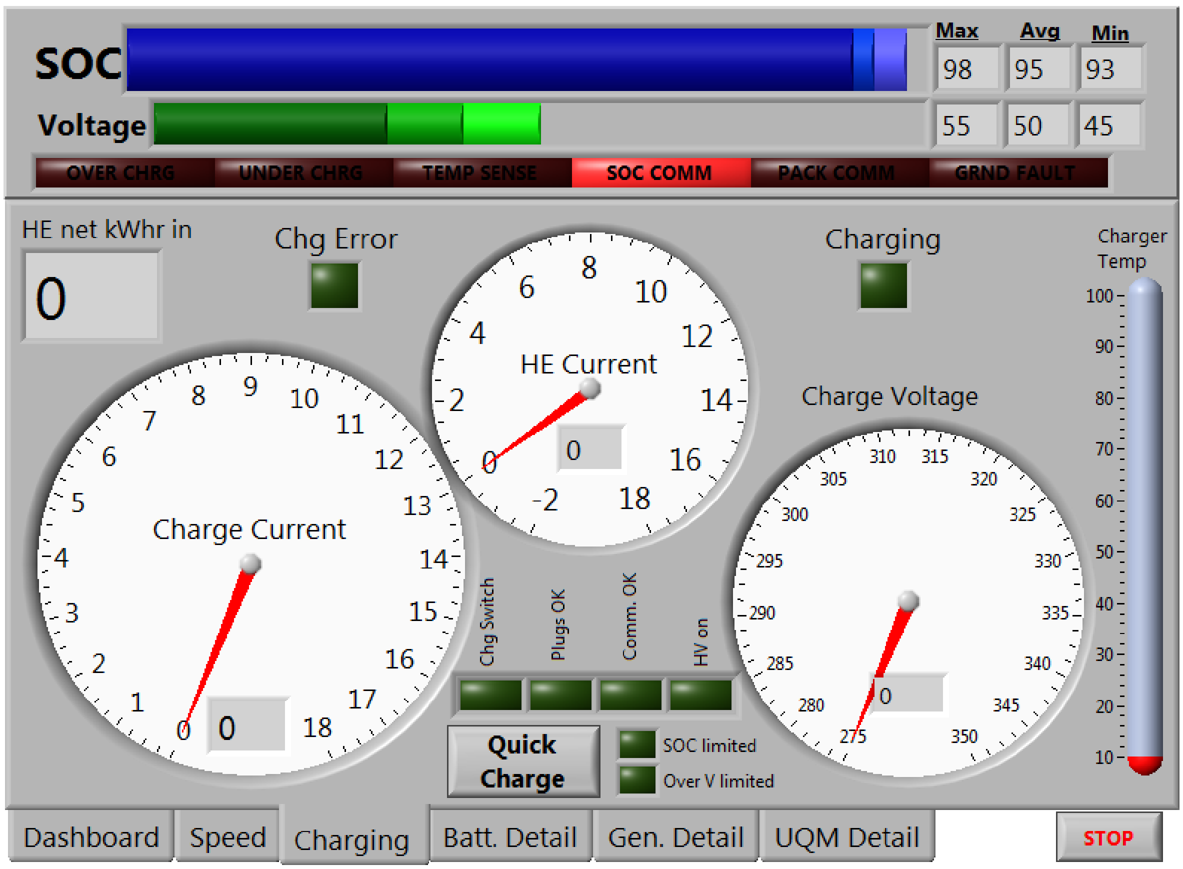
Lastly I have a large LED labeled "Engine Started" near the bottom center. This led blinks for ten seconds before the engine starting procedure is initiated. This blinking is meant to get the driver's attention and warn him of the significant noise that is about to begin. The engine pushed to the very rear of the engine compartment and is quite noisy when operational especially compared to the electric operation of the car. This could be very distracting if it is started while the driver is concentrating on a difficult curve or focused on maintaining a specific speed. The led is on solid when the engine is started and generating.

4.4.3 Speed Tab: Durability and Non-Emissions Sensitive Tests



The "Speed" tab is designed to give the driver the minimal required information needed to drive the car safely and ensure none of the power train elements are damaged. This screen is used in competition for the endurance course where vehicle efficiency is not measured and the driver must maintain a high rate of speed as well as navigate a complex road course. This screen is also used for dynamic safety tests such as emergency lane change, 0-60mph and 60-0 tests. The need for this screen was identified after our first round of emergency lane change tests where we ran into the glare and readability problems causing the driver to enter the maneuver at a higher than necessary speed. This speed, like on the Dashboard, is rounded to the nearest mph while taking up nearly 30% of the screen area. The battery summary display remains on the top so the driver can check battery health during an appropriate time.

4.4.4 Charging Tab: Used only with Plug-in Charger



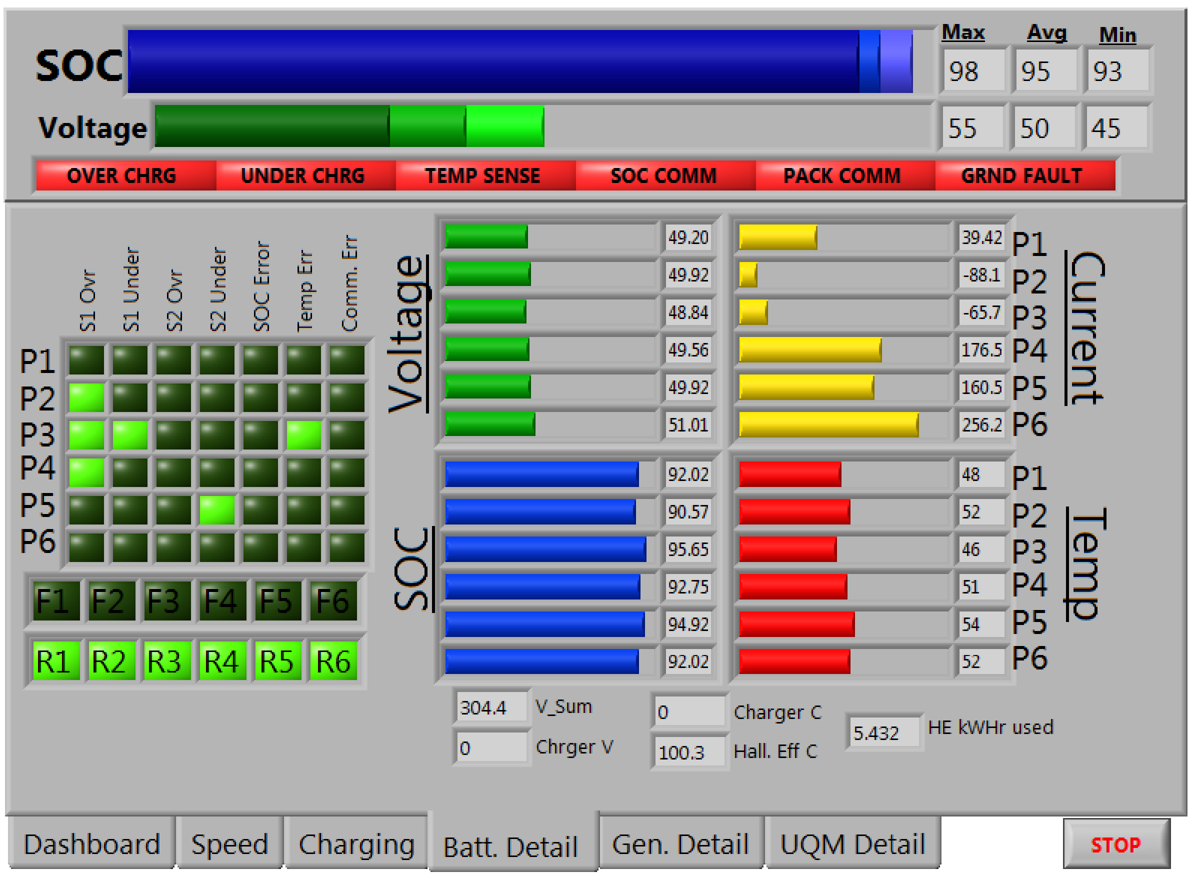
The "Charging" tab is used only used when the high voltage charger is being plugged in and started. This tab has three large dials giving the charge current and voltage reported by the charger as well as the Hall Effect current (HE Current). The Hall Effect current is reported for its significance as the batteries reach near full SOC. There will be some high voltage load while charging mainly from the rear DC/DC converter which could be as high as 1 amp. As the power being used to charge the batteries is decreased, this load will play a more significant portion of the charger current. Therefore it is important to see the current that is actually being delivered into the batteries.

There are various LEDs throughout the tab. Chg Error lights up if the charger itself reports an error (either over current, voltage, temperature or CAN timeout). The Charging led is lit when high voltage is on, and the charger is plugged in, configured properly, and enabled. The four horizontal leds near the middle of the tab give the status of the charger setup procedure. If the charger switch in the rear of the car is on then “Chg Switch” led is lit. if both plugs are properly inserted then the “Plugs OK” led is lit. Once communication between the charger and cRIO is established the “Comm. OK” led is lit and finally when the driver turns on the high voltage and the pack relays are all properly closed, the “HV on” led is lit meaning the vehicle is ready to begin charging.

The two lower leds “SOC limited” and “Over V limited” indicate whether charger power is being throttled by the battery SOC or voltage limits this is currently not implemented in software but the display is setup to accept the information)

The only touch screen to cRIO control is the “Quick Charge” button which forces the charger to charge at full power (18 amps) regardless of SOC or error state. This was implemented in case we have erroneous communication from the batteries that pre-maturely disable the charger.

4.4.5 Batt. Detail Tab: Shows Complete BMS data



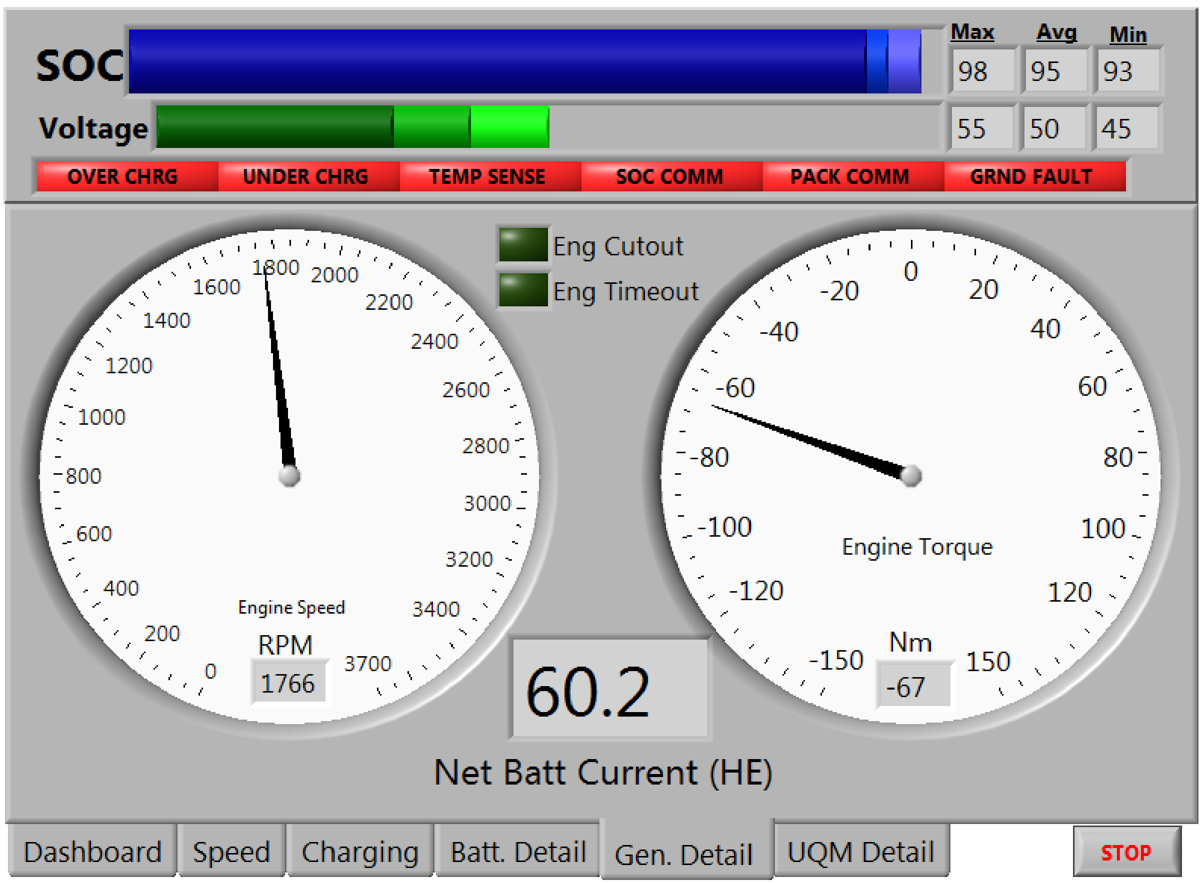
The “Batt. Dtail” tab is used for debugging potential battery problems without requiring vehicle shutdown. It displays nearly all information given by the new battery CAN messages, with the exception of giving the maximum temperature per pack instead of each temperature sensor per pack (2).

Voltage, current, SOC, and max temperature are displayed for each pack using horizontal progress bars as well as numeric displays much like the battery summary display bars at the top of the screen. The scroll bars are used to allow the reader to quickly identify a pack or data point that is inconsistent with the other packs and may be an incorrect value, or the sign of some larger problem. The numeric displays for these parameters are given in case the reader wants to take detailed data logs or perform calculations based on the values.

The table of leds at the middle right of the screen give each of the 7 possible errors for each pack. These values are ORed across each pack to generate the red leds on the battery summary display. The leds below this table with labels "F#" and "R#" represent whether the fan (F) for pack # is on, and if the relay (R" is closed for pack #).

Finally numeric displays for other relevant information is provided at the bottom of the screen such as the sum of all the pack voltages (V_Sum), the charger voltage and current (Chger V), (Chger C), and the Hall Effect current and estimated kWHr used.

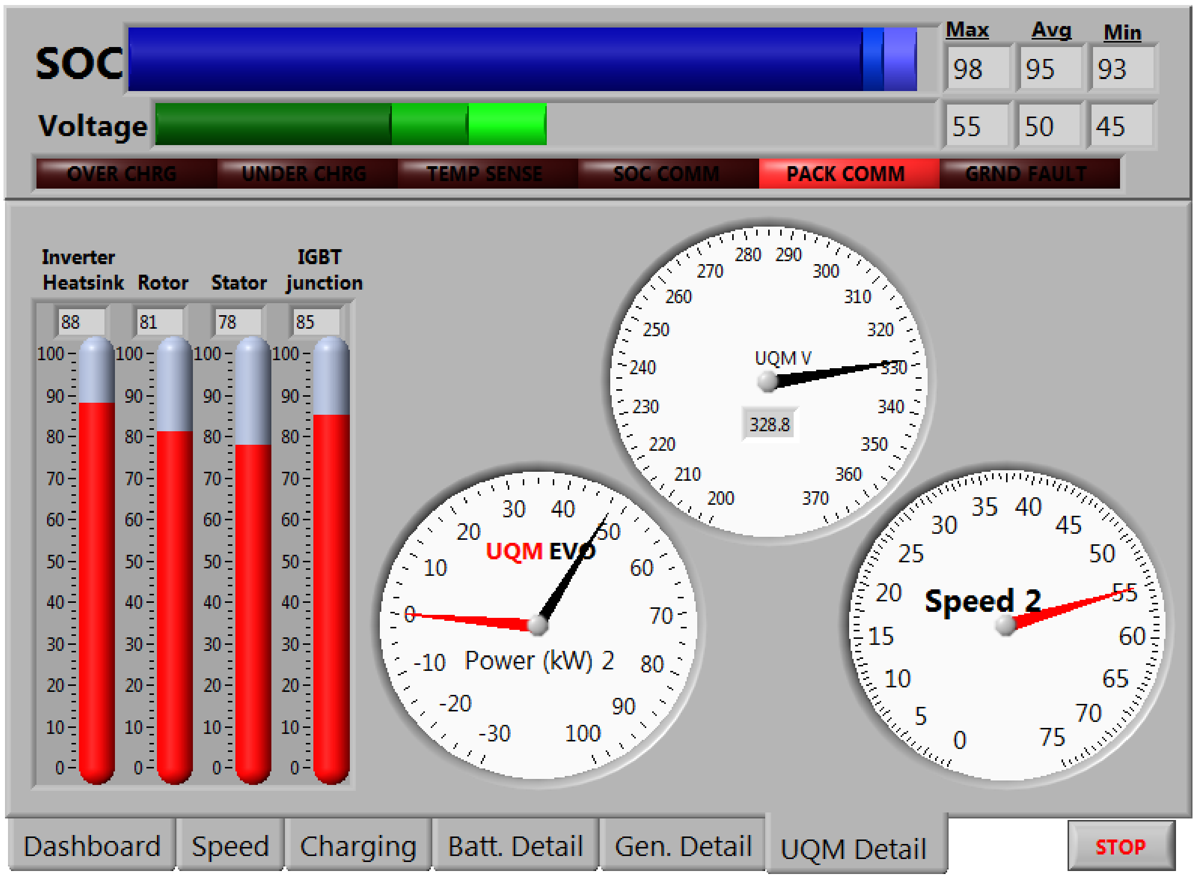
4.4.6 Gen. Detail Tab: Detailed Genset Information



The "Gen. Detail" tab is used to give the limited information available for the genset. We get actual engine speed which is given by the EVO generator and applied engine torque which the cRIO is requesting from the generator. These values are given as needle displays in order to visually determine the stability the feedback control algorithm. The Hall Effect current is also displayed which gives the net current delivered to the battery. This is important to monitor when debugging the genset, especially when the vehicle is under way as the batteries could still be sourcing power if the uqm power is greater than genset power.

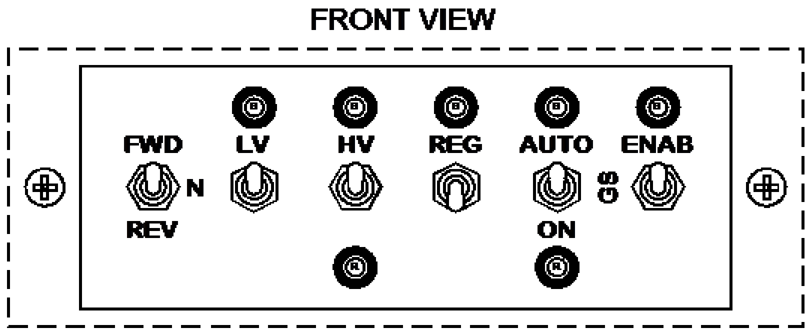
Lastly, there are two leds which light if a genset error is displayed. The "Eng Cutout" signifies that the engine rpm exceeded our rev limit causing the genset to be shut down. "Eng Timeout" signifies that the EVO tried to start the engine but it did not turn over within the allotted time.

4.4.7 UQM Detail: detailed UQM information



The "UQM detail" has four temperature meters giving the four reported UQM temperatures, two from the inverter, and two from the motor. The vehicle speed, UQM voltage and instantaneous UQM power (along with EVO power) are given as dial indicators to be consistent with the displays on the Dashboard.

4.5 Dashboard Switch Panel



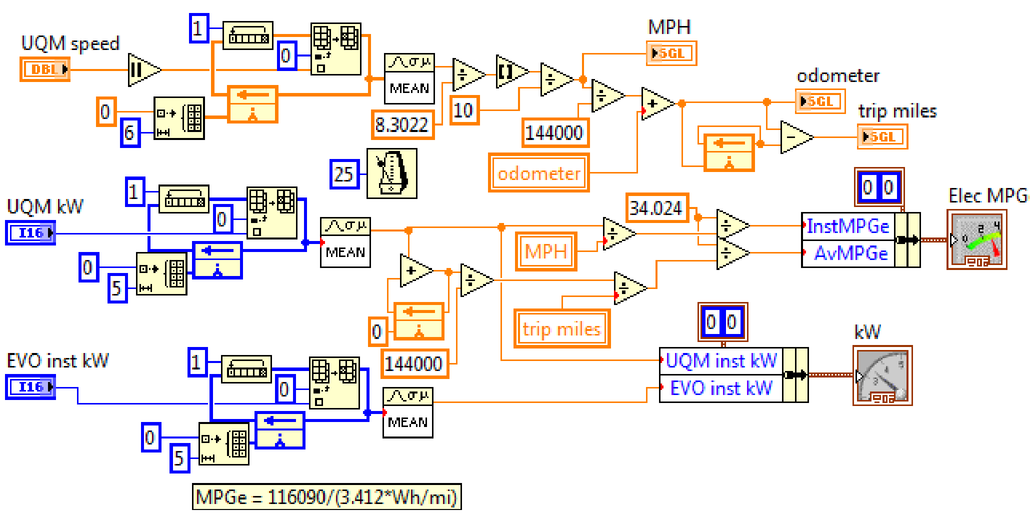
Dash Switch Panel

The figure above shows the dashboard switch panel used to control the hybrid drivetrain. The leftmost switch selects the direction of travel. The "LV" switch is used as the key turning on power to the cRIO, BMS, touchscreen and other vehicle controls. The "HV" turns on the high voltage batteries by closing the relays within the packs and cycling through the soft-start control. While the high voltage is in the process of opening or closing the led will flash. This tells the driver when it is safe to either turn off the car or begin driving. The "Reg" switch enables and disables the regenerative braking. This was a PIAXP requirement in order to test the braking distance under mechanical brakes only.

The remaining two switches control the operation of the genset. The switch, when in the "Auto" position allows the genset to automatically start when the state of charge drops below 35%, when in the "On" position the genset will start immediately regardless of the SOC. The rightmost switch labeled "Enab" enables the genset when up and disables / forces it off when disabled. This switch supersedes the functionality selected by the "Auto/On" switch.

4.6 User Interface Data Sender

The cRIO performs the data conversion needed to generate, speed, odometer, UQM and EVO power averaging and Electrical MPGe calculations. This is done on the cRIO instead of the touchscreen as the data update speeds are much faster on this device and timing is much more accurate, as we do not have transmission delay / packet errors to deal with.



Telemetry Conditioning and Sender LabVIEW Code

Originally we directly send vehicle speed and power but found that the data is too noisy to be useful or readable. Therefore the motor speed and power are averaged over six or five cycles respectively. This gives more stable results while still maintaining a fast update speed as the code runs every 25ms meaning the six data points for speed are refreshed every 150ms. Since our vehicle has direct drive, meaning the gear ratio between the UQM driveshaft and wheels remain the same, vehicle speed can be determined by simply dividing the driveshaft speed by the gear ratio and scaling to get mph. This speed is then integrated (via sampling) to get the distance travelled.

To calculate our electrical MPGe we use the formula given in the PIAXP requirements document:

$$MPGe = \frac{BTU_{gallon\_of\_gasoline}}{BTU_{WHr} \times \frac{WHr}{mi}} = \frac{116,090}{3.412} \times \frac{mi}{WHr} = 34.024 \times \frac{mi}{kWHr}$$

To get instantaneous MPGe we use vehicle speed (in miles per hour) and UQM power (in kW):

$$MPGe_{inst} = 34.024 \times \frac{mi}{Hr} \times \frac{1}{kW_{UQM}}$$

The average MPGe uses the original formula using our odometer reading to give us the miles travelled and the integral of UQM power to give us our kWHr of energy consumed. Note that both of these values are not exactly accurate as they do not take into account power consumed by the DC/DC converters, or inefficiencies within the battery pack and generators. But these values are only used for the driver to reference roughly as he drives around the track and are not intended to use for data collection purposes. The driver merely needs to know if he is driving too aggressively and is well below target, or if he is driving conservatively enough where we are likely meeting our MPGe requirements.

5 Selected Low Voltage Electrical Hardware

On top of the standard equipment and functionality available on cars today such as a radio, power windows, lighting, and the instrument cluster mentioned above we also had to have a complex network of various sensors and controls such as a ground fault detection system. These required numerous circuits to be scattered throughout the car to interface with the microcontroller.

5.1 cRIO IO interface boards

As mentioned throughout this report, the cRIO is an integral part of vehicle control system. Appendix 8.9.5 shows a list of the analog and digital input and outputs used to interface the vehicle with the cRIO. Nearly each one of these required an IO interface board to both condition the signals being sent, and protect the cRIO from erroneous or dangerous behavior on one of the connecting wires. There are over 21 of these IO modules which are described in detail in Appendix sections 8.4 through 8.7.

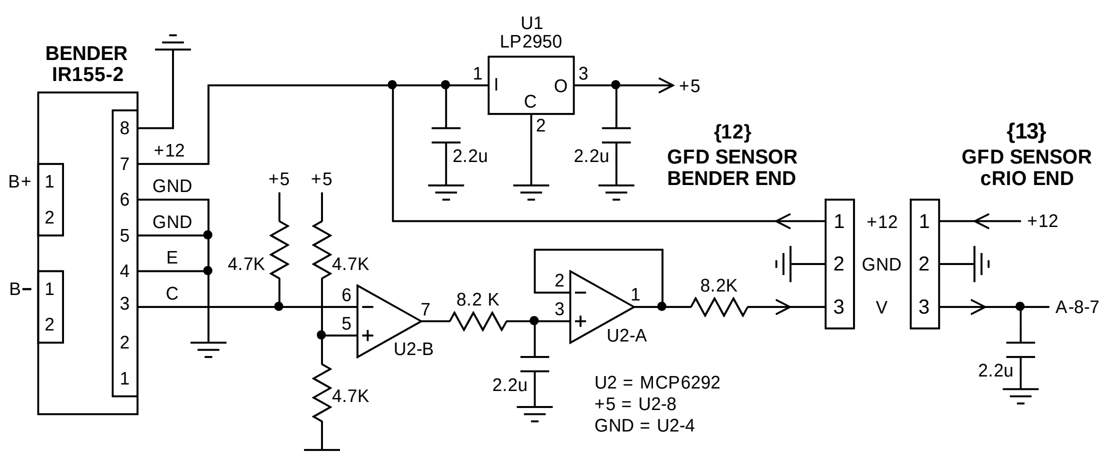
Many of these circuits interface with sensors such as hall effect current instruments, analog pedals, and the GFD. These sensors require accurate and speedy measurements of analog signals which are used to ensure vehicle safety and driver control. Since the car contains high power switching power supplies, we had to design our circuitry to be as noise immune as possible. One of the design tools we used to aid our noise immunity was having the reference ground and power to these sensors be supplied by these interface boards. This meant that the sensors were floating relative to the frame and other electronics around them. With the sensor and ground wires bundled together any noise would be common mode and affect the reference ground and signal wire equally. Therefore the voltage difference between the two would remain accurate even if the sensor wires had induced noise up to many volts. Of course we also used R-C low pass filters to reduce any differential high frequency noise present on the wires.

We also designed these interface boards to protect the expensive cRIO modules from human error, such as plugging in connectors incorrectly, and device failure. The analog and digital inputs on the cRIO are high impedance devices and have their own built in voltage protection which will try to clamp the voltage on one of the input pins to +/- 10 volts. Of course these modules can only absorb less than 100mA and would be overwhelmed if someone inadvertently plugged the +12 volts from the battery directly into one of these ports. Therefore all IO's have a series resistor on the order of ~5kΩ. This limits the current required to clamp the voltage to 10s of mA.

5.2 Ground Fault Detector Support Circuitry

Our Vehicle includes a ground fault detection (GFD) system provided by Bender which is capable of detecting leakage resistances as high as 10MΩ. Having a GFD is not only a PIAXP requirement but also a standard safety feature on most high voltage, high power electric vehicles. Our specific system is set to warn the driver if the leakage resistance drops below 1KΩ/Volt or ~320KΩ for our vehicle. This is double the PIAXP requirement. The output of the GFD is an opto-isolated PWM signal. In order to simplify the software required to measure this PWM circuit we simply convert it to an analog signal where a 0% duty cycle would be 0 volts and a 100% duty cycle would be 5 volts. This can be directly read by the cRIO's analog inputs and converted to a duty cycle by simply dividing the voltage by 5.

We use two rail to rail op-amps to convert the pulse to an analog signal. The first (labeled U2-B) is used to give very sharp edges to the output pulse. This is then low pass filtered with a resistor and capacitor which is then fed into a voltage follower (labeled U2-A) giving a powerful driver for the analog signal. Finally this is again low pass filtered by the 8.2K resistor next to the GFI (on circuit {12}) and the capacitor on the cRIO side (circuit {13}).



Schematic of GFD Support Circuitry

The GFD error can be seen in the *Battery Summary Display* (4.4.1) as the rightmost red warning LED.

6 Data and Results

Our vehicle drove hundreds of miles starting in mid November of 2009. These multiple tests demonstrate the functionality of the vehicle and the success of my software and hardware designs and implementation. During most of our driving tests we recorded data such as battery voltage, current, and various temperatures and torques. We also documented our driving and lab tests on YouTube. These videos were required as proof of a functional vehicle for the PIAXP competition.

6.1 Data Log

Since our first driving test we have logged data every ¼ second. This has resulted in hundreds of thousands of lines of data. We had a modeling team dedicated to analyzing this data for accuracy, consistency, and to suggest areas of improvement. They established during our most lengthy test that we were able to achieve between 110 and 115 MPGe under electric drive. Of course the genset is a less efficient source of electricity than the wall charger so this milage would be reduced under extended driving but demonstrates that we are very near the required efficiencies.

An excerpt of this data log is shown in appendix 8.1.5. It is time stamped by time of day in ¼ of seconds (for example 12:00 noon is 172800). The battery voltage in this excerpt is low, in fact during this except we only had 1 battery reporting voltage. We can see that the UQM voltage is a more appropriate overall voltage. The "BattErr" encodes the battery errors discussed in *Section 3.2*. Every two digits represent the errors from a specific battery back. We can see that all packs had some error.

This data gives some verification to the vehicle performance and behavior. We can see the UQM current is negative when the torque is negative and the voltage drop grows as current increases. Also the UQM temperature rises as power is demanded.

6.2 Driving Videos

During all of our driving tests ,up to the first round of competition, I rode in the front passenger seat and monitored vehicle parameters to ensure the vehicle remained safe and quickly diagnose any software or hardware problems. The videos below are in chronological order and show the progression both of our vehicle completeness and

Initial Driving Tests

Link: http://www.youtube.com/watch?v=EAc8JdjI3C4

This video was taken on our second day of testing in mid November. We drove with an electric only drivetrain meaning the engine and EVO electric generator were not installed in the car. You can see most of the internals as these tests took place before our body panels were made.

Vehicle 0-60 Test

Link: http://www.youtube.com/watch?v=a7yqwNK-3v4

This very brief video shows the power of our UQM drive motor by squealing the tires during one of our acceleration runs.

Vehicle 60-0 mph braking test

Link: http://www.youtube.com/watch?v=enwTPrC-b44&feature=related

This brief video shoes our car testing our braking distance. As you can hear and see the combination of regen and mechanical brakes allows us to decelerate very rapidly meeting the minimum braking distance. Although both in this video and our test during competition we locked up the tires, so having anti-lock brakes would improve our braking distance and vehicle control.

Battery Thermal Management auto Shutdown video

Link: http://www.youtube.com/cornell100mpg#p/a/797335AC564DCDB1/1/daW6CtOcTSM

This video was taken as part of the PIAXP second technical deliverable. We had to demonstrate our vehicle properly shut down under a battery thermal event. We heated one of the battery temperature sensors with a small heat gun in order to slowly increase the sensors temperature. The vehicle limits battery power by lowering the maximum allowable current going through the UQM (see *section 4.1.2*)

The current limit while the temperature rises is sudden (drops from 300 amps down to 0). As the temperature sensor cools you can see the multiple steps described in *section 4.3.1*.

Genset Startup and Battery Charging

Link: http://www.youtube.com/watch?v=x4-nnMT2IrY

This video was taken during winter break before the Spring 2010 semester. It shows our first successful operation of the geneset. You can hear the motor begin to turn the engine over and then roar to start. The camera then shows the cRIO reading the engine speed through the EVO sensor. The green LED next to the speed sensor labeled "Cutout" shows that the cRIO properly detected the engine has started and limits forward torque to 0Nm so the generator does not over-rev the engine.

When I move the "EVO Fwd Tq" slider to negative values the generator begins resisting the engine and passing current through the batteries. This is demonstrated both by the current meter reading and the battery SOC rising.

Drive-by Road Test

Link: http://www.youtube.com/watch?v=GdQzZabLxp4

This video shows our car driving up game farm road at a high rate of speed after we passed NYS inspection and became road legal.

Dynamic Avoidance Test with spinout

Link: http://www.youtube.com/watch?v=CDALpcKcMdM&feature=related

This dramatic video was taken during our first round of competition. It shoes our car going through the dynamic avoidance test. The vehicle entered the maneuver at a higher than required speed and ended up spinning out. What happens after the camera drops is the vehicle skidded sideways and began "hopping".

In the opinion of one of the safety judges, our car came very close to flipping over and said that hopping just precedes vehicle rollover. This test resulted in the "Speed" tab for the touch screen described in *section 4.4.3* allowing the driver to clearly see the vehicle speed and increase his speed very slowly not risking a repeat of this near catastrophe.

7 Vehicle Analysis and Conclusions

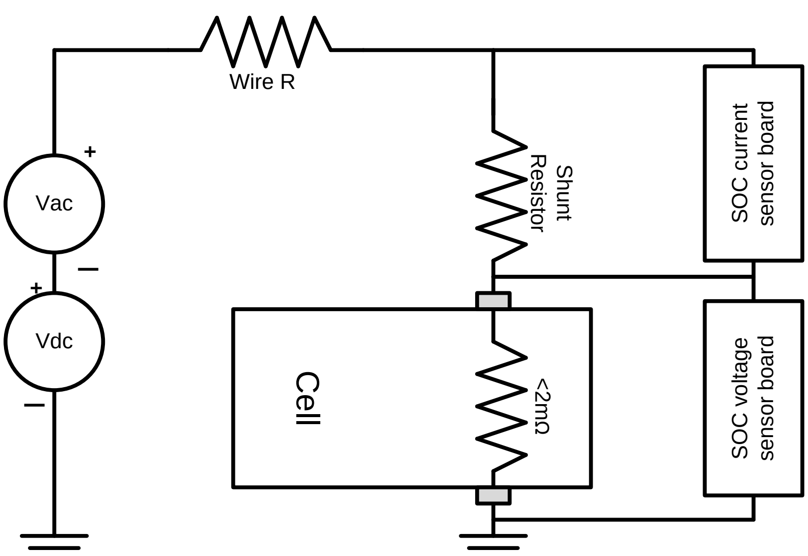
We encountered a few problems with our electronic system where I had to analyze possible sources of errors and rule them out. We had concerns about noise transmitted through the high voltage cables from the switching power inverters from the UQM as well as the switching supplies in the DC/DC converter. I also discuss an analysis of the problem that caused us to withdraw from the competition.

7.1 Potential Switching Noise Interference on Battery Control Boards

Skin Effect is the tendency of an AC current to distribute itself near the surface of a conductor. This results in an increased resistance as frequency increases, as the skin depth (depth of conductor used) decreases. This increased resistance results in higher AC frequencies having a smaller and smaller effect on battery voltage. In the case of the UQM's switching frequency, this is 0.06% of the resistance of the wire under a DC load.

Diagram of worst-case scenario:

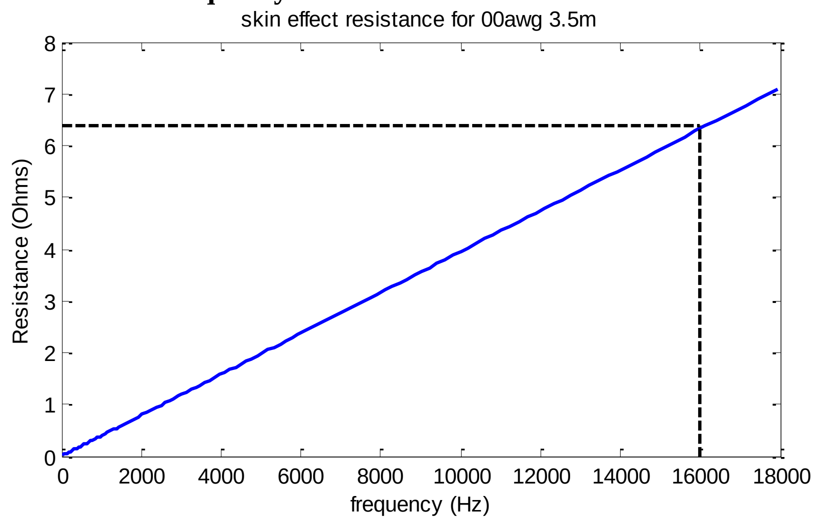
The diagram shows a single cell with the negative terminal at a fixed ground. It is being excited by a voltage source with a DC and AC component. *(Note the cell voltage is reduced to 0 for simplicity)*



Switching Noise from UQM inverter

At the switching frequency of the UQM (16kHz). The wire resistance is ~6ohms. This resistance is 3,000 times the internal cell resistance. Therefore if the UQM was outputting a 300 volt AC swing the cell voltage would raise and lower by 0.1volts

A graph of the wire resistance frequency is:



Formulas of wire resistance for frequency

$$R = \frac{\rho}{\delta}\left(\frac{L}{\pi(D-\delta)}\right) \approx R = \frac{\rho}{\delta}\left(\frac{L}{\pi(D)}\right) \qquad Skin\_Depth = \delta = \left(\frac{\rho}{\pi \cdot f \cdot \mu}\right)$$

f = frequency

D = conductor diameter

L = 1-way wire length

Resistivity and Permeability of Copper:

$$\rho = 1.72\times10^{-8}\,\Omega\text{m}$$

$$\mu_{Cu} = 4\pi\times10^{-7}\,\text{Hm}^{-1}$$

Skin Depth Calculation for inverters with 00awg wire

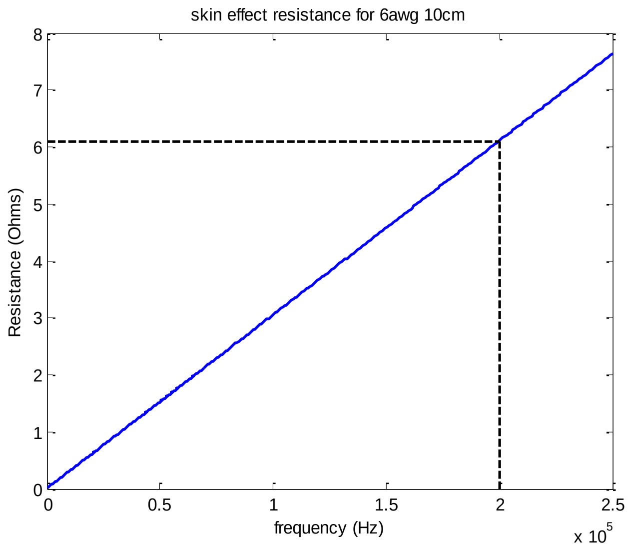
$$Skin\_Depth = \delta = \left(\frac{1.72\times10^{-8}\,\Omega\text{m}}{\pi\cdot 16\text{kHz}\cdot 4\pi\times10^{-7}\,\text{Hm}^{-1}}\right) \qquad R = \frac{1.72\times10^{-8}\,\Omega\text{m}}{\delta}\left(\frac{3m}{\pi\cdot 1.113\times10^{-2}\,m}\right)$$

$$R = 6.37\Omega$$

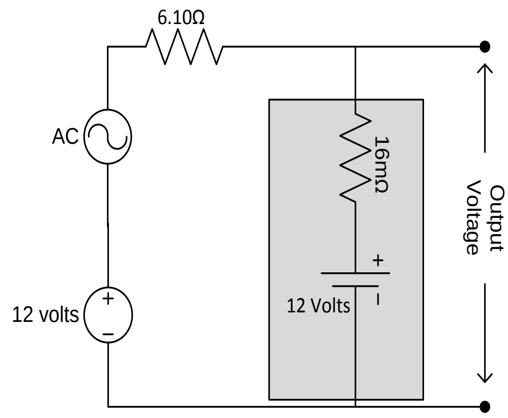
Skin Depth Calculation for DC/DC converter with 6awg wire

$$Skin\_Depth = \delta = \left(\frac{1.72\times10^{-8}\,\Omega\text{m}}{\pi\cdot 200\text{kHz}\cdot 4\pi\times10^{-7}\,\text{Hm}^{-1}}\right) \quad R = \frac{1.72\times10^{-8}\,\Omega\text{m}}{\delta}\left(\frac{0.1\text{m}}{\pi\cdot 4.1148\times10^{-3}\,\text{m}}\right)$$

$$R = 6.10\Omega$$



Skin Effect Resistance



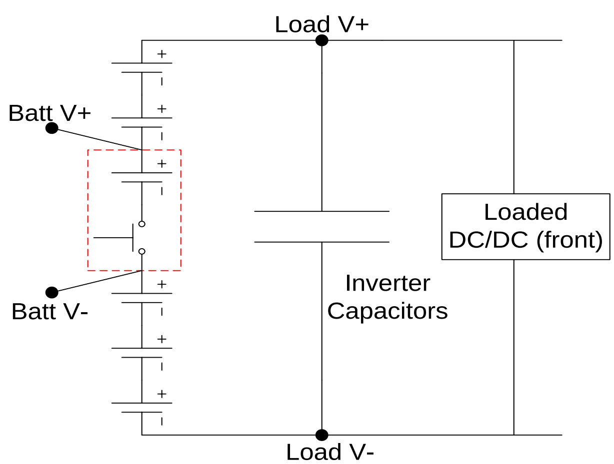
Circuit diagram for Low voltage AC side

At the switching frequency of the DC/DC converter (200kHz). The wire resistance is also ~6ohms. This resistance is 750 times the internal resistance of the lead acid battery (specified at 8mΩ). I am doubling this resistance just for a safety factor. The output ripple of the DC/DC converter is specified as 120mV although even if the output ripple was 12 volts the Output Voltage node would only oscillate by 31mV, meaning if the DC/DC converter was operating at its specified ripple, the experienced AC component would only be 310µV.

We can see from the analysis of the motor inverters' switching noise that any 200kHz noise will be completely swamped by the skin effect resistance of the 00 wire it must pass through which is roughly 1 meter in length for the DC/DC converter closest to the battery.

7.2 Potential explanation for SOC Board Damage During Knockout Stage

In the document below I give a possible reasoning for why the SOC boards were damaged a few seconds after a pack relay opened.



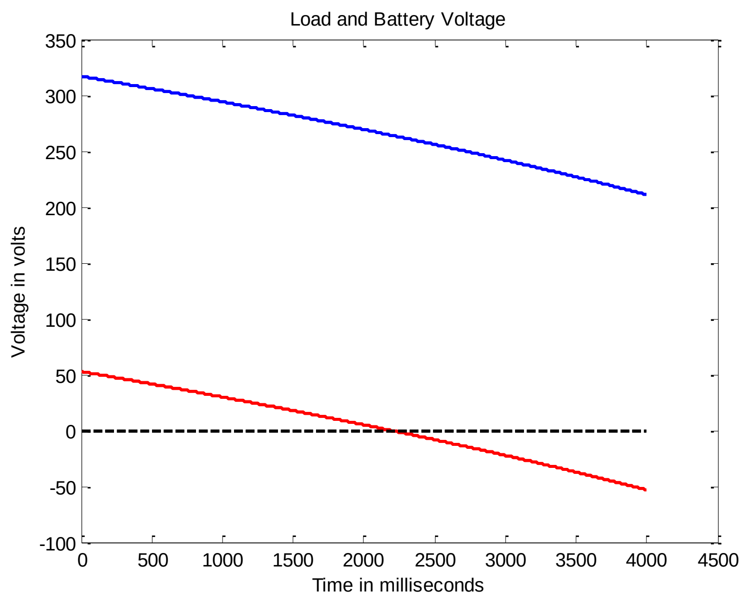
Simplified Schematic of HV System

The diagram above shows a schematic for the batteries, Inverter capacitors, and front DC/DC load. I selected Pack 3 to be the pack whose relay opens erroneously. When the relay is closed, the voltage across **Load V** is ~317V (the pack voltage). The voltage across **Batt V** when the relay is closed is held constant by the cells at ~53 volts.

I noticed that the front DC/DC remained on even after the relay opened. This meant that it continued to supply power to its own fan and the UQM pump. We previously estimated the load of the pump and fan to be around 100 Watts. Once the relay opens the batteries no longer maintain the voltage across the capacitor and the DC/DC load begins to drain the capacitor energy and thus lowers the voltage.

With only 1 relay open we note that **Batt V-** will be held 158.5 volts (3 packs) above **Load V-** and **Batt V+** will be 105.7 volts (2 packs) below **Load+** as the voltage across the Inverter Capacitors drops the voltage between **BattV+** and **Batt V-** will decrease and go negative once **Load V** drops below 264.2 volts.

A plot of **Load V** (in blue) and **Batt V** (in red) is shown below.

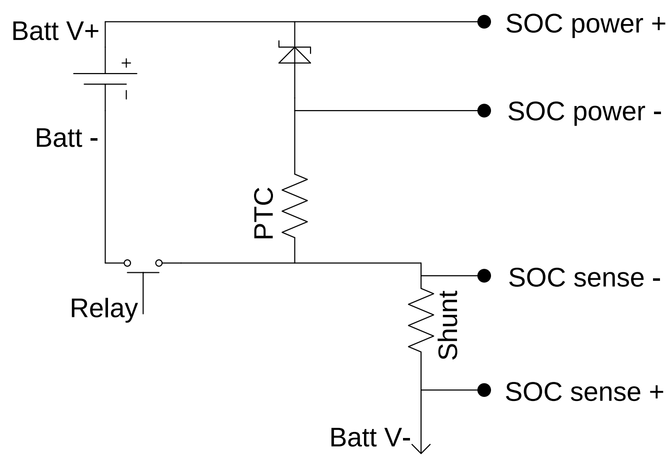


The calculated voltage drop is given by the following equations:

$$I = \frac{DC_{power} \approx 100W}{V_{capacitor}}$$

$$I = C\frac{dV_{capacitor}}{dt} \Rightarrow dV_{capacitor} = \frac{I \cdot dt}{C}$$

We can see that after about 2.25 seconds the voltage across the selected SOC board goes negative. The schematic below highlights the internals of the battery affecting the SOC board:



Battery Sensor Schematic

As shown in the graph the Batt V- potential is actually higher than **BattV+** this means that the zener diode is forward biased (acts as a short). Current will pass through the PTC causing it to raise its resistance while the voltage across SOC power will be small (on the order of a couple of volts) due to the forward bias of the diode. Therefore the voltage between **SOC sense-** and **SOC power-** will grow as voltage drops and will be roughly equal to **Batt V- - Batt V+**. As the graph shows, this voltage grows to near 50 volts within 3.5 seconds and a reverse polarity to what the sensor boards are designed for.

It is likely that this voltage potential would cause damage to the circuitry within the integrator and could cause the damage we experienced. It also has a similar time delay to what we experienced, where the loud pop occurred a couple seconds after the relay opened.

During normal operation the soft-start relays opened first disconnecting the capacitors from the batteries protecting against this behavior.

This of course does not answer the question of *why* the relay opened and I think we will have to test the DC/DC as well as well as the signal quality on the RS485 data line to and possibly more to discover why the problem occurred.

7.3 Conclusion

Overall our vehicle was a large success. Within one year we were able to bring the project from a few scattered components and a rolling chassis to a fully functional series hybrid vehicle. We met all competition and FMVSS requirements and had a road legal car that drove around campus with ease. It could accelerate faster than a Toyota Camry, and drive over 40 silent miles on battery power alone. We were rushed throughout the entire process and had very limited time for testing and optimization. In the end our withdrawal may have been avoidable with a few months to fully test all subsystems both independently and working in unison. This hopefully will be a task the team will tackle, and be able to gather significant data that our series hybrid vehicle can easily achieve 100 miles to gallon equivalency while offering a driving experience similar to marketable, production vehicles we are accustomed to.

8 Appendices

8.1 MATLAB Code

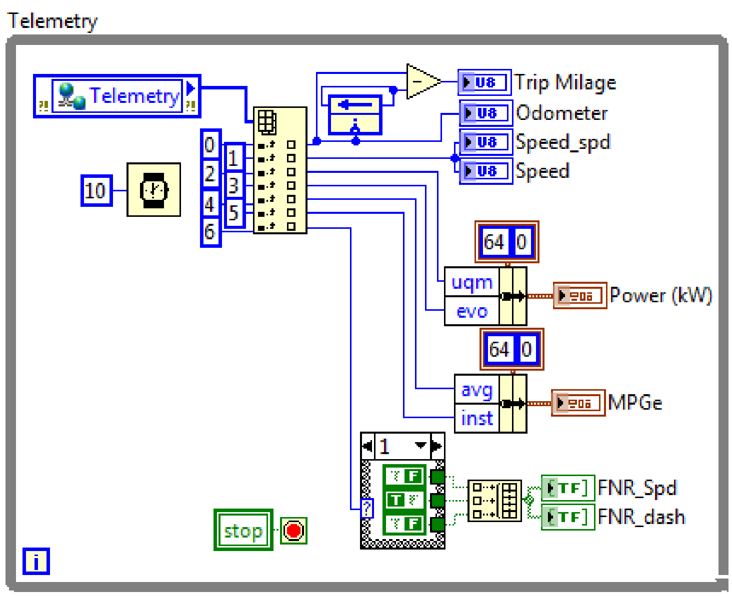
8.1.1 Skin Effect MATLAB Code

```
%skin effect

p = 1.72e-8;       %ohm meters
u = (4e-7)*pi;     %henrys per meter
D = 1.113e-2;      %diameter of 00 wire in meters
L = 3.5;             %1-way length of 00 in meters

f = 16000;         %frequency

Rlist = p*L/(pi*(D/2)^2);
Flist = 0;
for it = 1:(round(sqrt(f))+8)
    f = it^2;
    Flist(it) = it;
    SkinD = p/(pi*f*u);

    R = p*L/(pi*D*SkinD);
    Rlist(it) = R;
end

figure(1)
plot((1:it).^2,Rlist,'LineWidth',2)

%========== Calculation for 12Volt side of DC/DC converter ===============

D6 = 11.1148e-3;     %diameter of 20 wire in meters
L6 = .5;             %1-way length of 20 in meters

f = 200000;        %frequency
fmax = round(sqrt(250000));
Rlist = p*L6/(pi*(D6/2)^2);
Flist = 0;
for it = 1:fmax
    f = it^2;
    Flist(it) = it;
    SkinD = p/(pi*f*u);

    R = p*L6/(pi*D6*SkinD);
    Rlist(it) = R;
end

figure(2)
plot((1:it).^2,Rlist,'LineWidth',2)
```

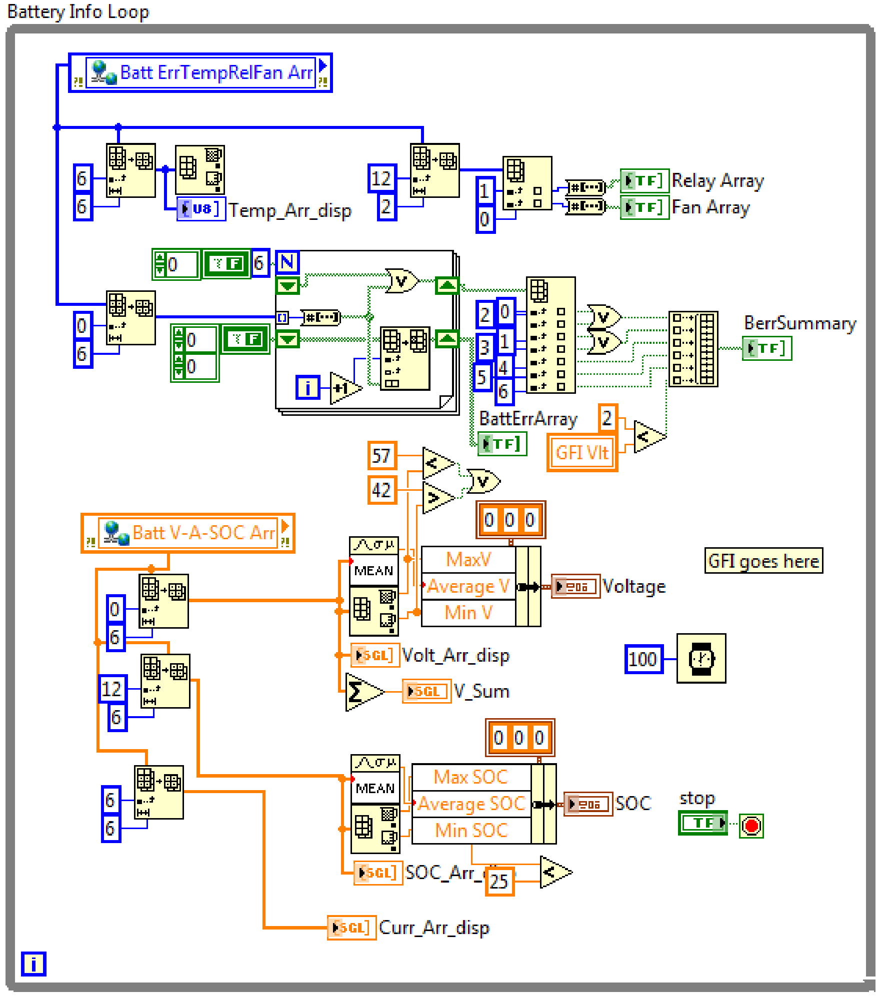
8.1.2 SOC damage capacitor discharge MATLAB code

```
F = 2*7290e-6; %farads
CapV(1)=317;

LVcurr=1.5+7;
LVpwr=LVcurr*12;

for t=1:4000
    I(t)=LVpwr/CapV(t);
    dv=I(t)/F*.001;
    CapV(t+1)=CapV(t)-dv;
end
figure(2)
plot(CapV,'-b','LineWidth',2)
hold on
plot(CapV-317*5/6,'-r','LineWidth',2)
hold on
line([0,4000],[0,0],'Color','k','LineStyle','--','LineWidth',2)
xlabel('Time in milliseconds')
ylabel('Voltage in volts')
title('Load and Battery Voltage')
```

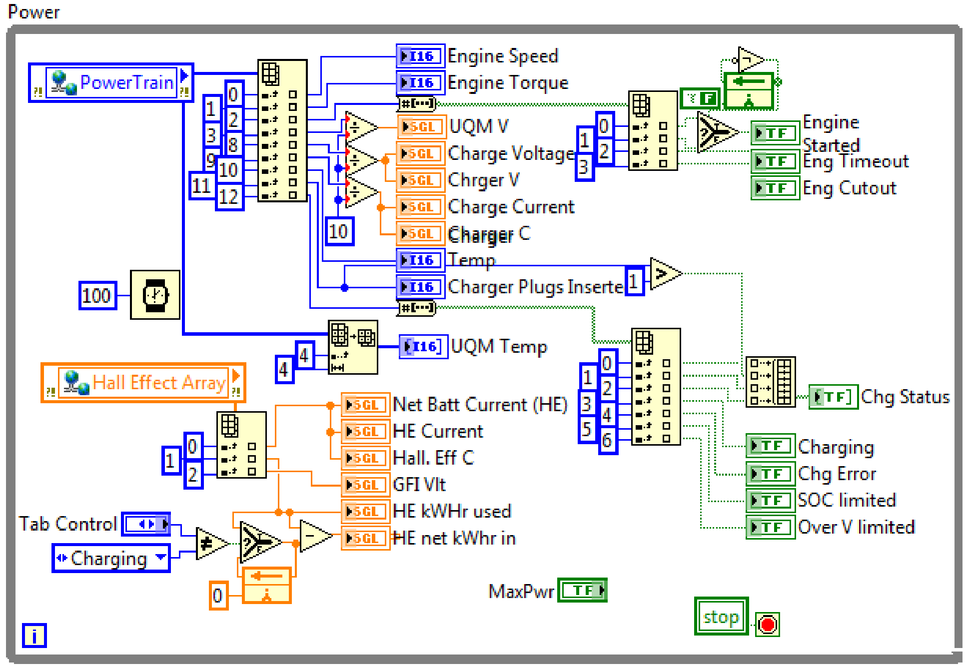
8.2 Touch Screen LabVIEW code



Battery Info Loop



Power



8.3 Touch Screen Network Variables

Variable Name: Batt ErrTempRelFan Arr
Data Type: U8 (unsigned 8-bit integer)
Number of Elements: 14

Index	**0-5**	**6-11**	**12**	**13**
Data	Pack 1-6 errors	Pack 1-6 temps	Pack Fans on	Pack Relays Closed

Variable Name: Batt V-A-SOC Arr
Data Type: Single (32-bit floating point)
Number of Elements: 18

Index	**0-5**	**6-11**	**12-17**
Data	Pack 1-6 Voltage	Pack 1-6 Current	Pack 1-6 SOC

Variable Name: Telemetry
Data Type: I16 (signed 16-bit integer)
Number of Elements: 7

Index	**0**	**1**	**2**	**3**	**4**	**5**	**6**
Data	Odometer	Speed	UQM kW	EVO kW	Avg MPGe	Inst MPGe	Direction

Variable Name: PowerTrain
Data Type: I16 (signed 16-bit integer)
Number of Elements: 13

Index	**0**	**1**	**2**	**3**	**4**
Data	Engine RPM	Engine Torque	Genset Status	UQM Voltage	Charger Voltage

Index	**5**	**6**	**7**	**8**	**9-12**
Data	Charge Current	Charge Temp	Charge Plugs	Charge Status	UQM Temps

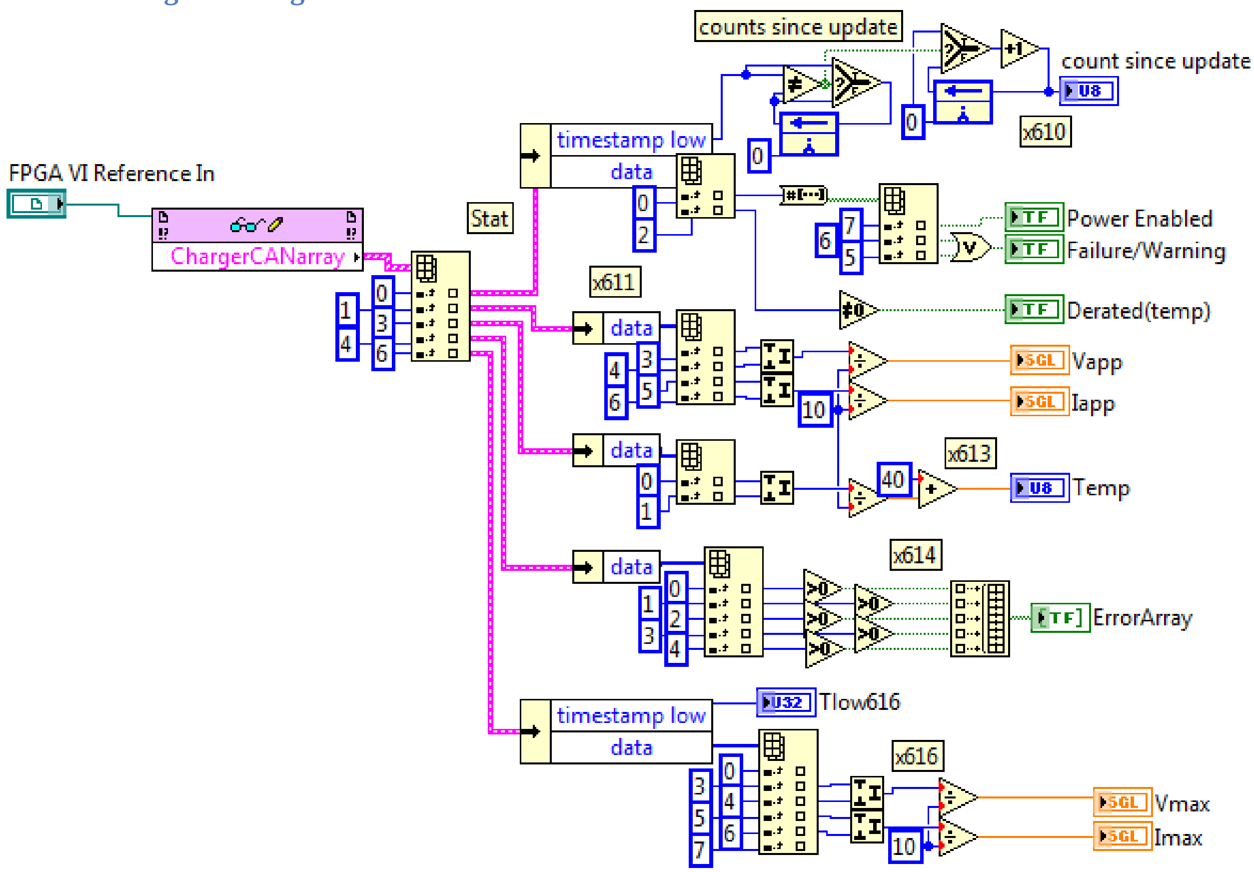
Variable Name: Hall Effect Array
Data Type: Single (32-bit floating point)
Number of Elements: 3

Index	**0**	**1**	**2**
Data	Hall Effect Current	GFI Voltage	Hall Effect kWhr

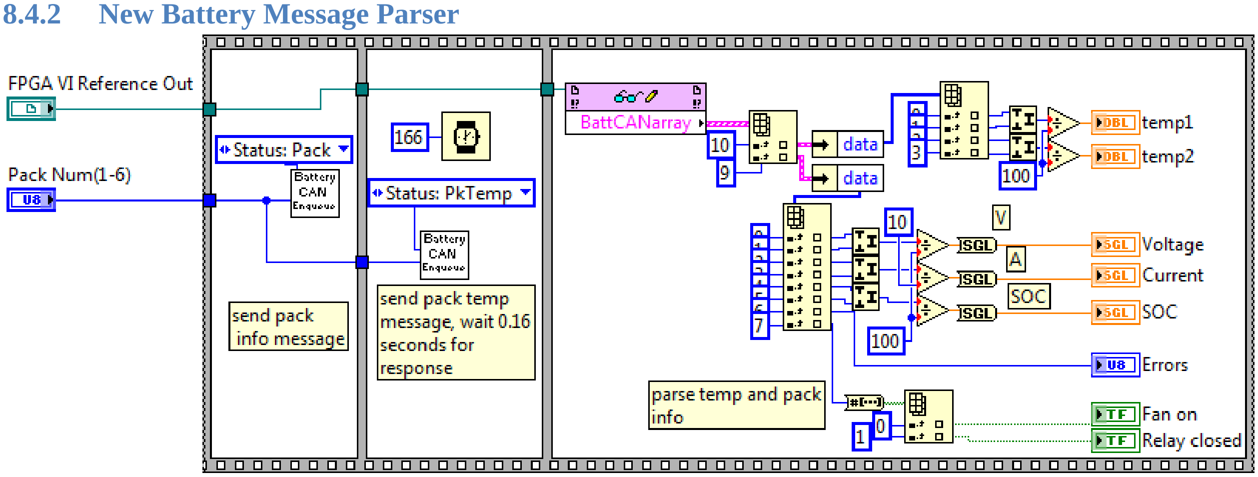
Table of Touchscreen Network Variables

8.4 Selected LabVIEW Code on cRIO

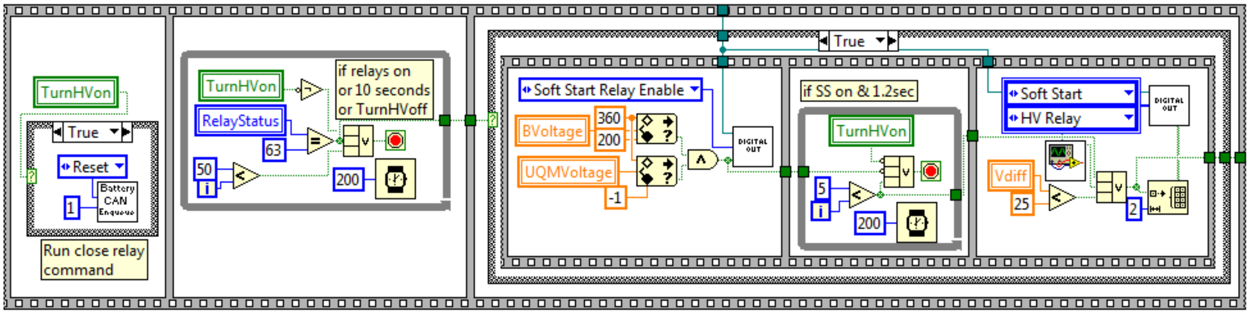
8.4.1 Charger Message Parser



8.4.2 New Battery Message Parser

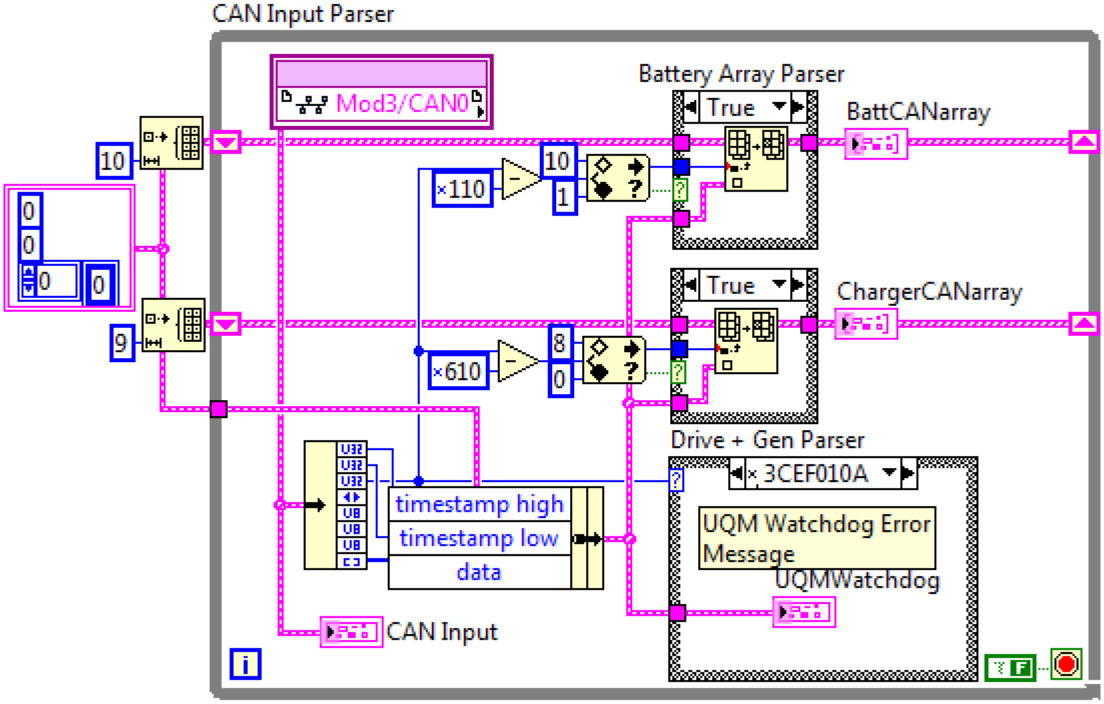


8.4.3 High Voltage On Sequencer



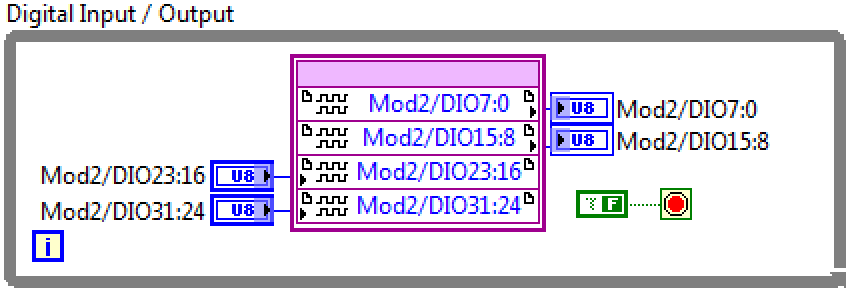
8.4.4 FPGA CAN Array Makers

CAN Input Parser

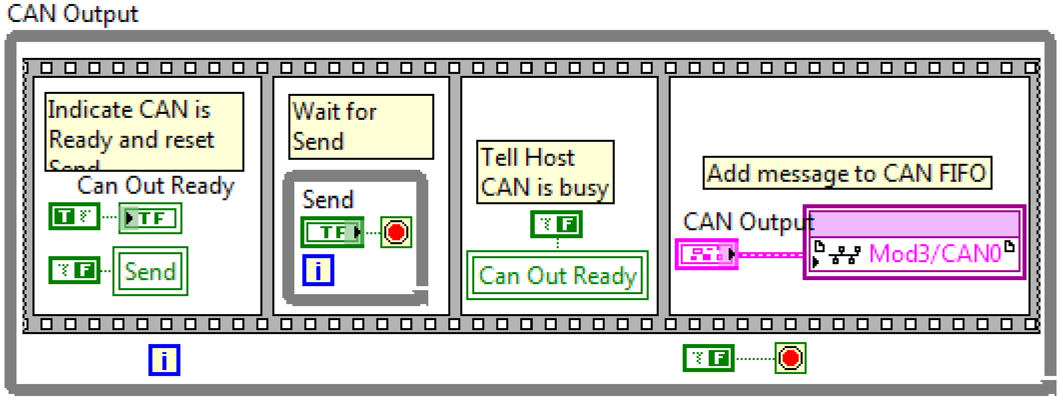


8.4.5 FPGA Digital IO Array Maker

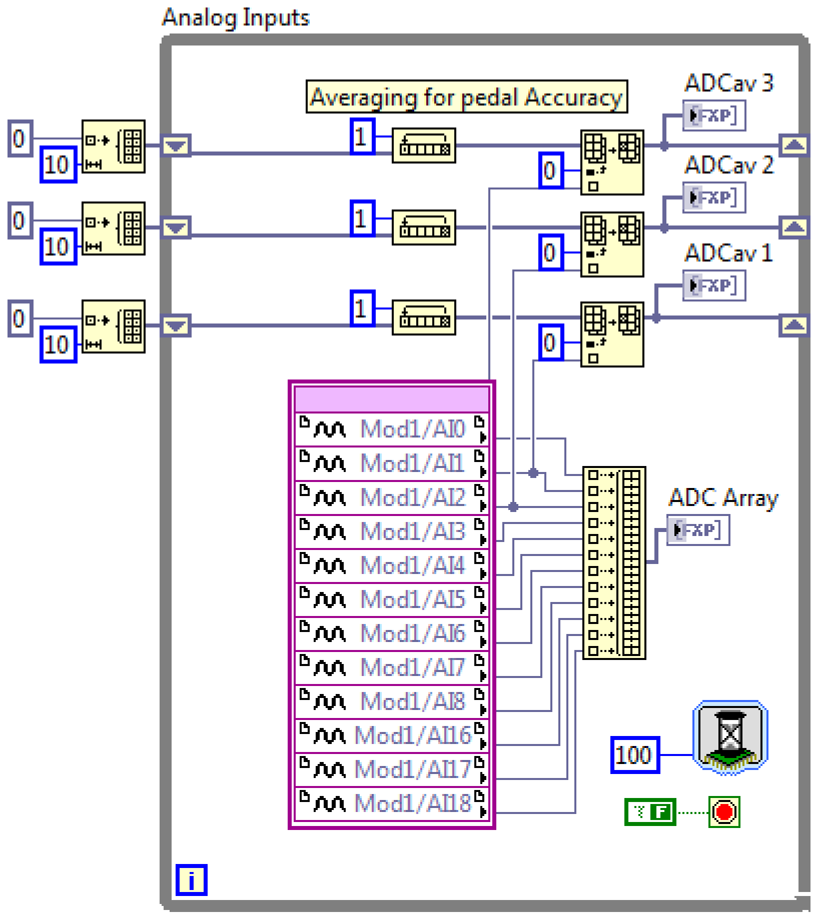
Digital Input / Output



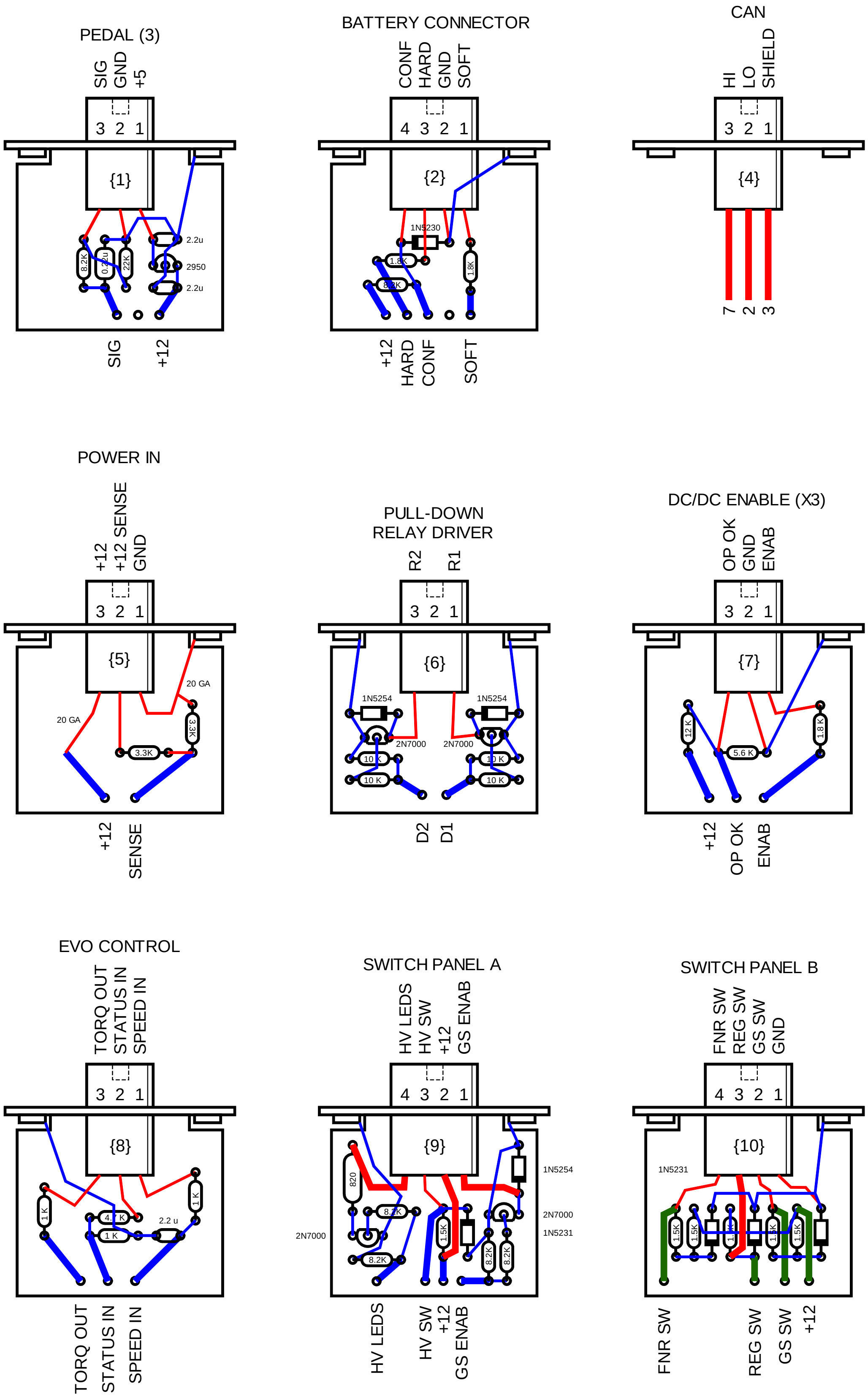
8.4.6 FPGA CAN Message Sender



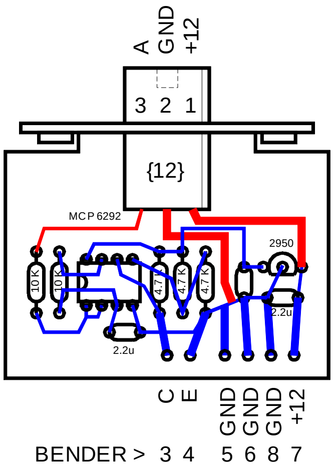
8.4.7 FPGA Analog Input Array Maker



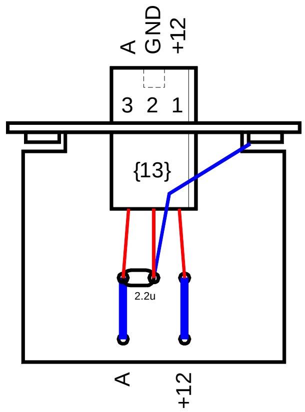
8.5 cRIO IO Modules Layout and Schematic



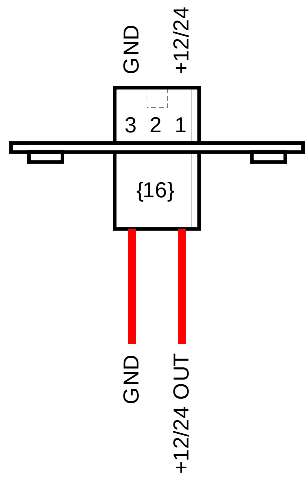
GFD SENSOR
BENDER END



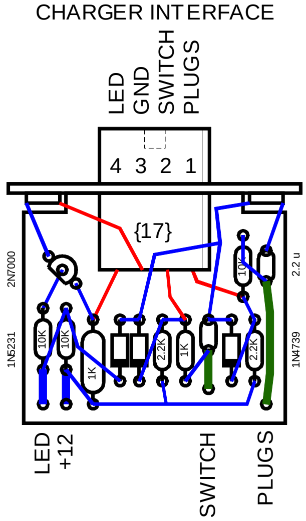
GFD SENSOR
cRIO END



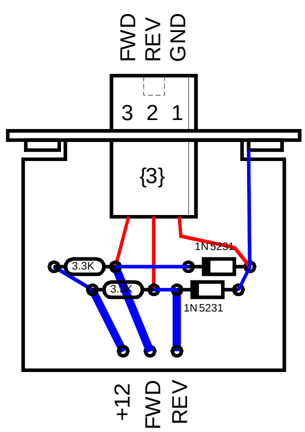
EVO/UQM INVERTER POWER



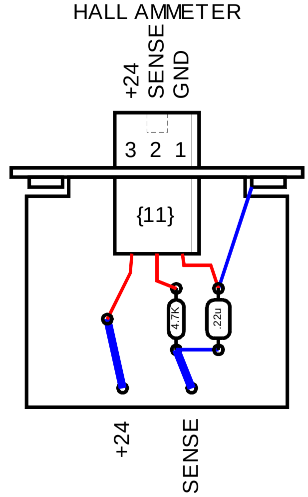
CHARGER INTERFACE



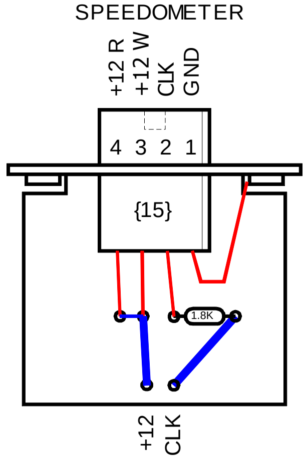
FWD/REV



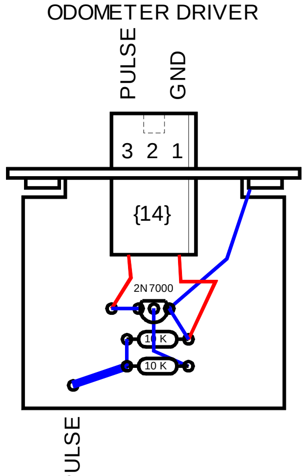
HALL AMMETER



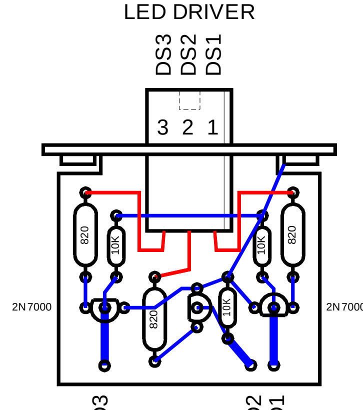
SPEEDOMETER



ODOMETER DRIVER

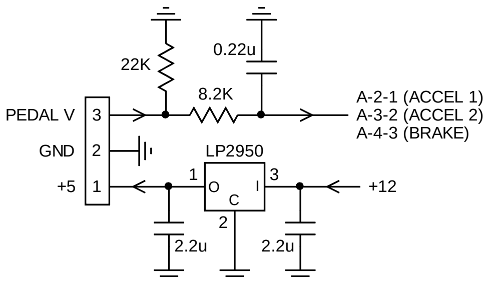


LED DRIVER

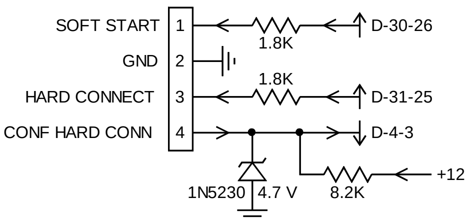


Selected cRIO IO Board Schematics

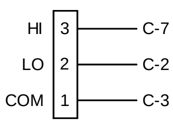
{1} PEDALS (X3)



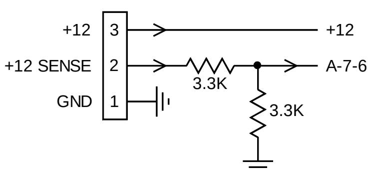
{2} BATTERY CONNECTOR BOX



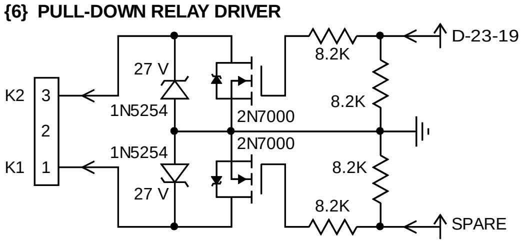
{4} CAN



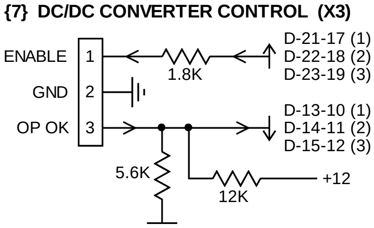
{5} POWER IN



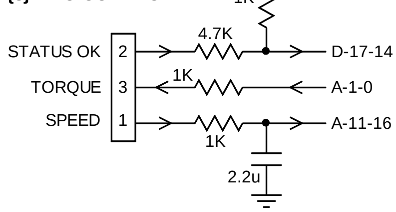
{6} PULL-DOWN RELAY DRIVER



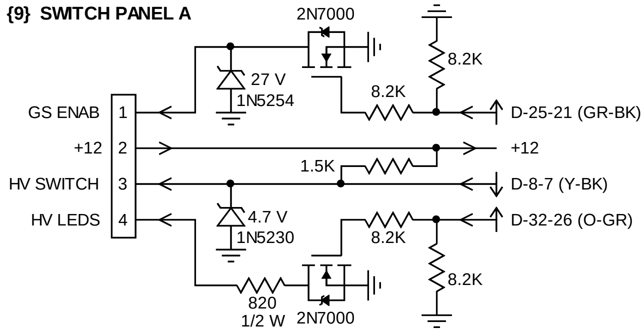
{7} DC/DC CONVERTER CONTROL (X3)



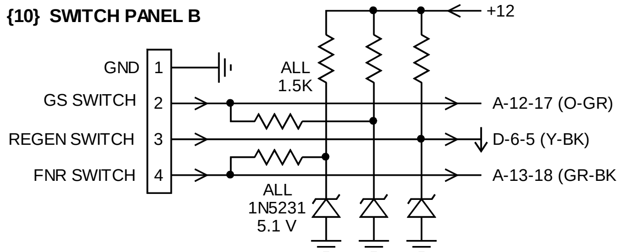
{8} EVO CONTROL



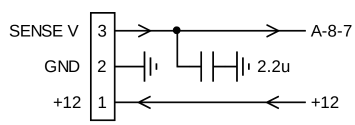
{9} SWITCH PANEL A



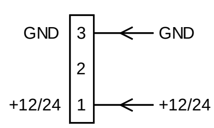
{10} SWITCH PANEL B



{13} GFD SENSOR

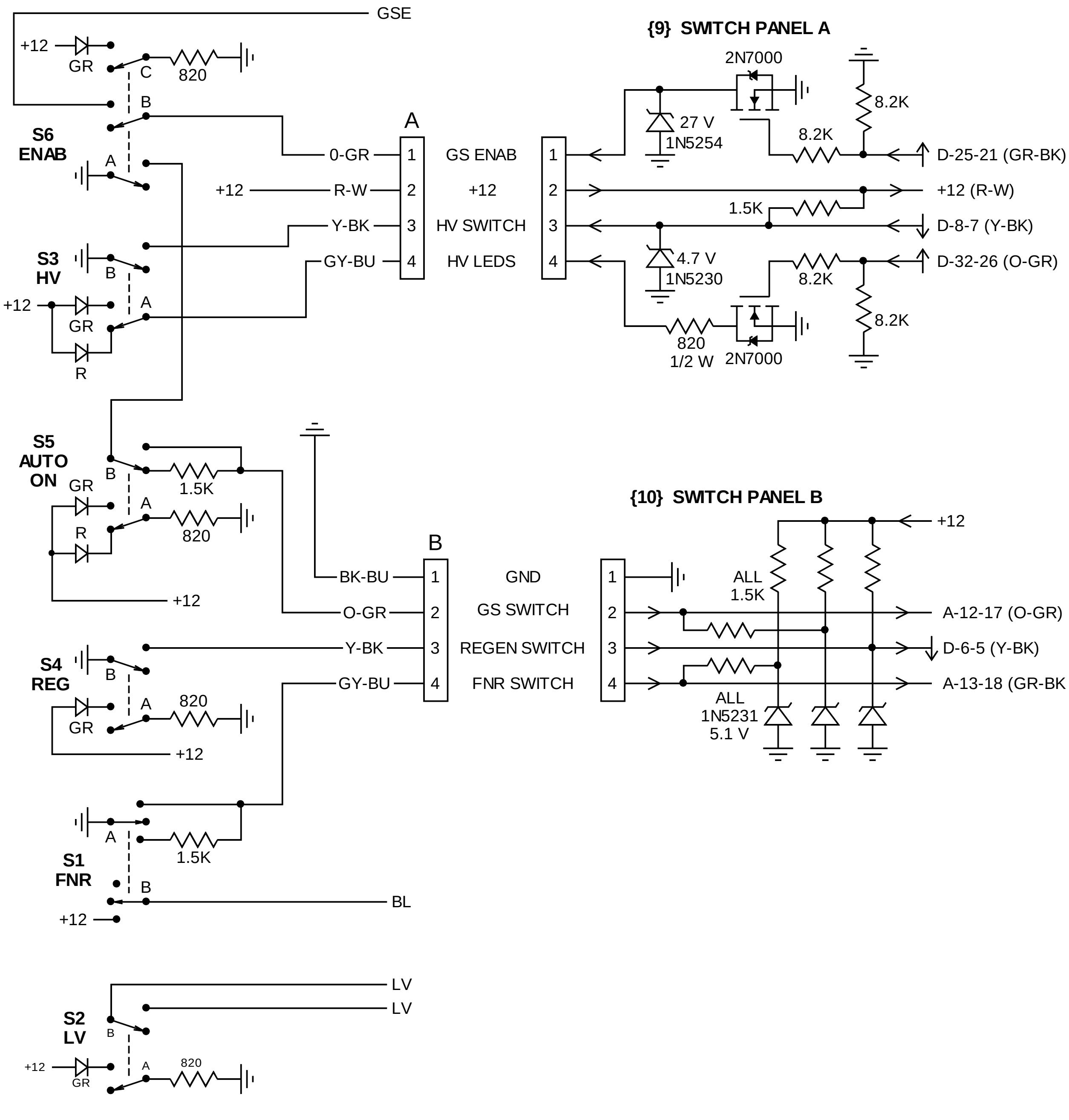


{16} EV0/UQM INVERTER POWER



8.6 Dashboard Switch Panel Schematic (w/ cRIO IO Modules)

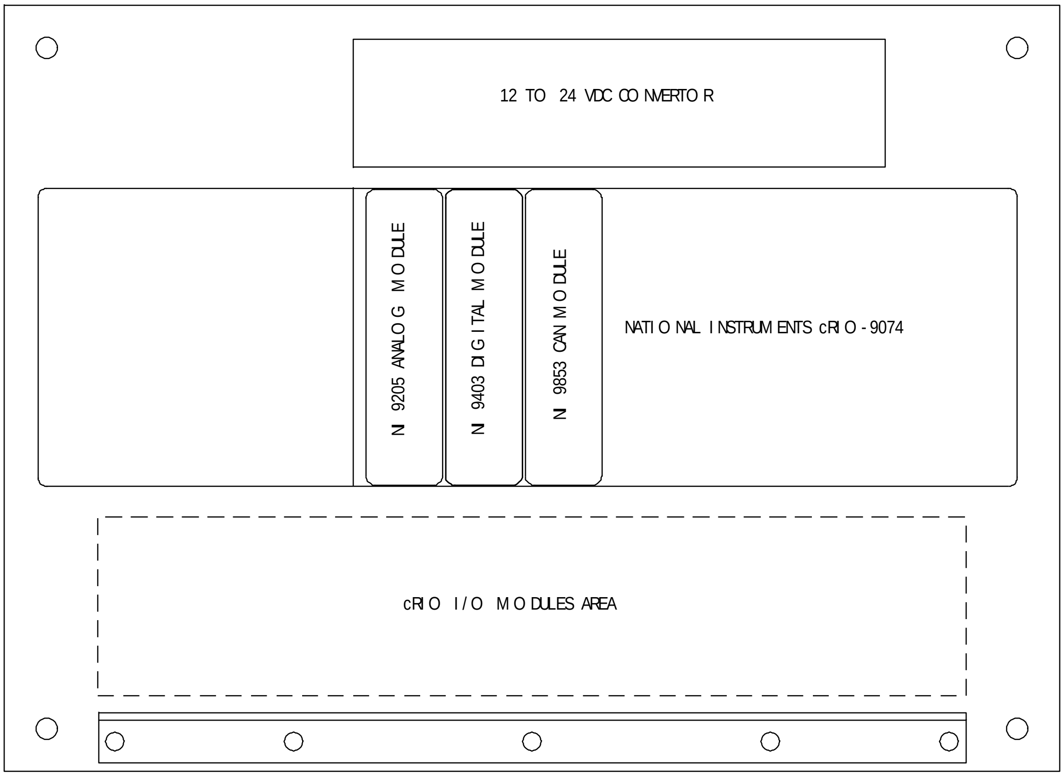
The Main Switch Panel schematic is on the left. For completeness the associated cRIO Interface Module schematics are shown on the right



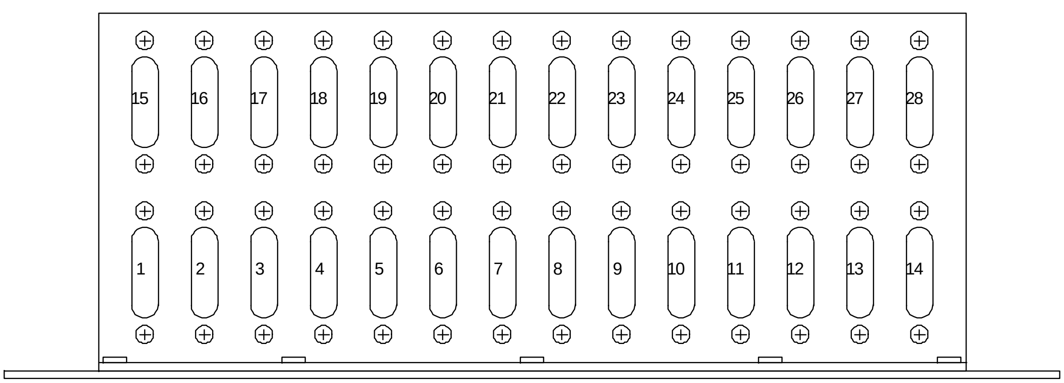
8.7 cRIO and IO Board Mounting and Numbering

The cRIO control unit is the central control for the entire car. It uses a National Instruments cRIO control box, which has many analog inputs, many digital inputs and outputs, and a CAN interface. Also contained in this cRIO control unit is a +12 VDC to +24 VDC up-converter to provide power to units requiring +24 power. In order to connect the cRIO inputs and outputs to signals, that are incompatible for direct connection to the cRIO, a multitude of independent I/O interface modules are incorporated. These are independent small circuit boards with a connector that are mounted in a slotted panel. This panel can accommodate up to 28 I/O interface modules.

MASTER CONTROL UNIT LAYOUT



cRIO I/O MODULE SLOT NUMBERS



8.8 I/O MODULE CONNECTOR LOCATIONS AND PIN ASSIGNMENTS

{n} indicates module design number
[D-n-b] indicates connection to cRIO digital I/O module, terminal n, logical bit b.
[A-n-b] indicates connection to cRIO analog Input module, terminal n, logical bit b.

1 Master Power Input {5}
- 1 Gnd in
- 2 +12 measured in (1/2) [A-7-6]
- 3 +12 power in

2 Accelerator Pedal 1 {1}
- 1 +5 out
- 2 Gnd out
- 3 Signal in [A-2-1]

3 Accelerator Pedal 2 {1}
- 1 +5 out
- 2 Gnd out
- 3 Signal in [A-3-2]

4 Brake Pedal {1}
- 1 +5 out
- 2 Gnd out
- 3 Signal in [A-4-3]

5 Battery Connect box {2}
- 1 Soft Start out [D-30-24]
- 2 Digital ground
- 3 Hard Connect out [D-31-25]
- 4 Confirmed in [D-4-3] **not used**

6 Forward/Reverse switch {3} **not used**
- 1 Gnd
- 2 Forward in [D-11-8]
- 3 Reverse in [D-12-9]

7 CAN UQM D-sub {4}

CAN	UQM	D-sub
1 Com [3]	H	3
2 Lo [2]	S	2
3 Hi [7]	T	7

8 Switch Panel A {9}
- 1 GenSet enable out [D-25-21]
- 2 +12 out
- 3 High voltage switch in [D-8-7]
- 4 High voltage LEDs out [D-32-26]

9 DC/DC converter enable 1 {7}
- 1 Enable out [D-20-16]
- 2 Gnd
- 3 Operating OK in [D-13-10]

10 DC/DC converter enable 2 {7}
- 1 Enable out [D-21-17]
- 2 Gnd
- 3 Operating OK in [D-14-11]

11 DC/DC converter enable 3 {7}
- 1 Enable out [D-22-18]
- 2 Gnd
- 3 Operating OK in [D-15-12]

12 2 Relay pull down {6}
- 1 Fan out [D-23-19]
- 2 NC
- 3 Spare [D-?-?]

13 EVO Generator control {8}
- 1 Speed in [A-11-16]
- 2 Status in [D-17-14]
- 3 Torque out [A-1-0]

14 EVO inverter power {16}
- 1 +24 out (no fuse)
- 2 NC
- 3 Gnd

18 Switch Panel B {10}
- 1 Gnd
- 2 GenSet switch position in [A-12-17]
- 3 Regen switch position in [D-6-5]
- 4 FWD/N/REV switch position in [A-13-18]

21 UQM inverter power {16}
- 1 +12 out (no fuse) to Amphenol pin N
- 2 NC
- 3 Gnd out to Amphenol pin K

22 Speedometer {15} **not used**
- 1 Gnd
- 2 Clk out [D-26-22]
- 3 +12 W
- 4 +12 R

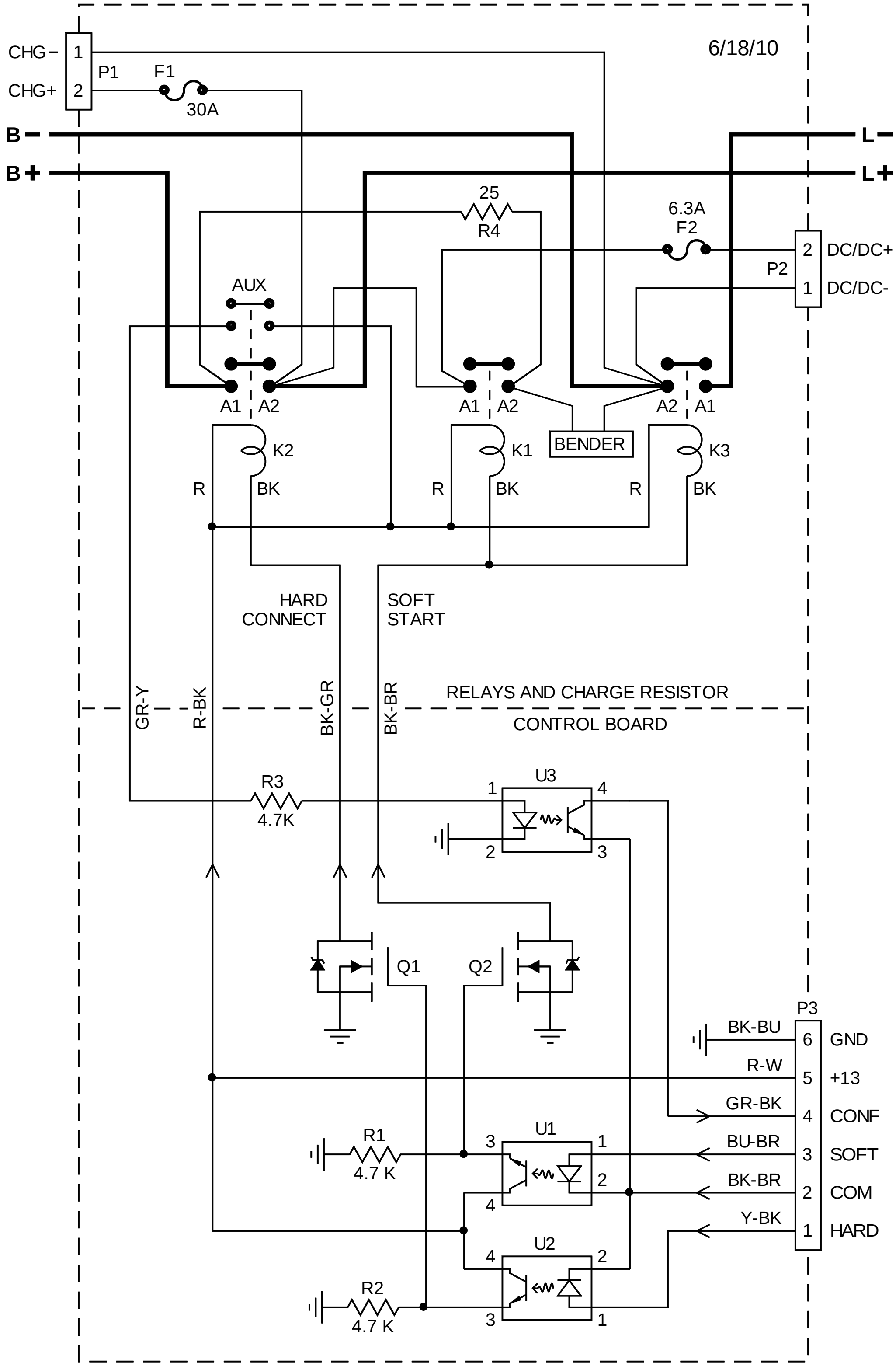
23 Odometer {14} **not used**
- 1 Gnd
- 2 NC
- 3 Clk out [D-27-23]

24 GFD Sensor {12}
- 1 +12
- 2 Gnd
- 3 Sense V in [A-8-7]

27 Hall Effect Ammeter {11}
- 1 Gnd
- 2 Sense in [A-6-5]
- 3 +24

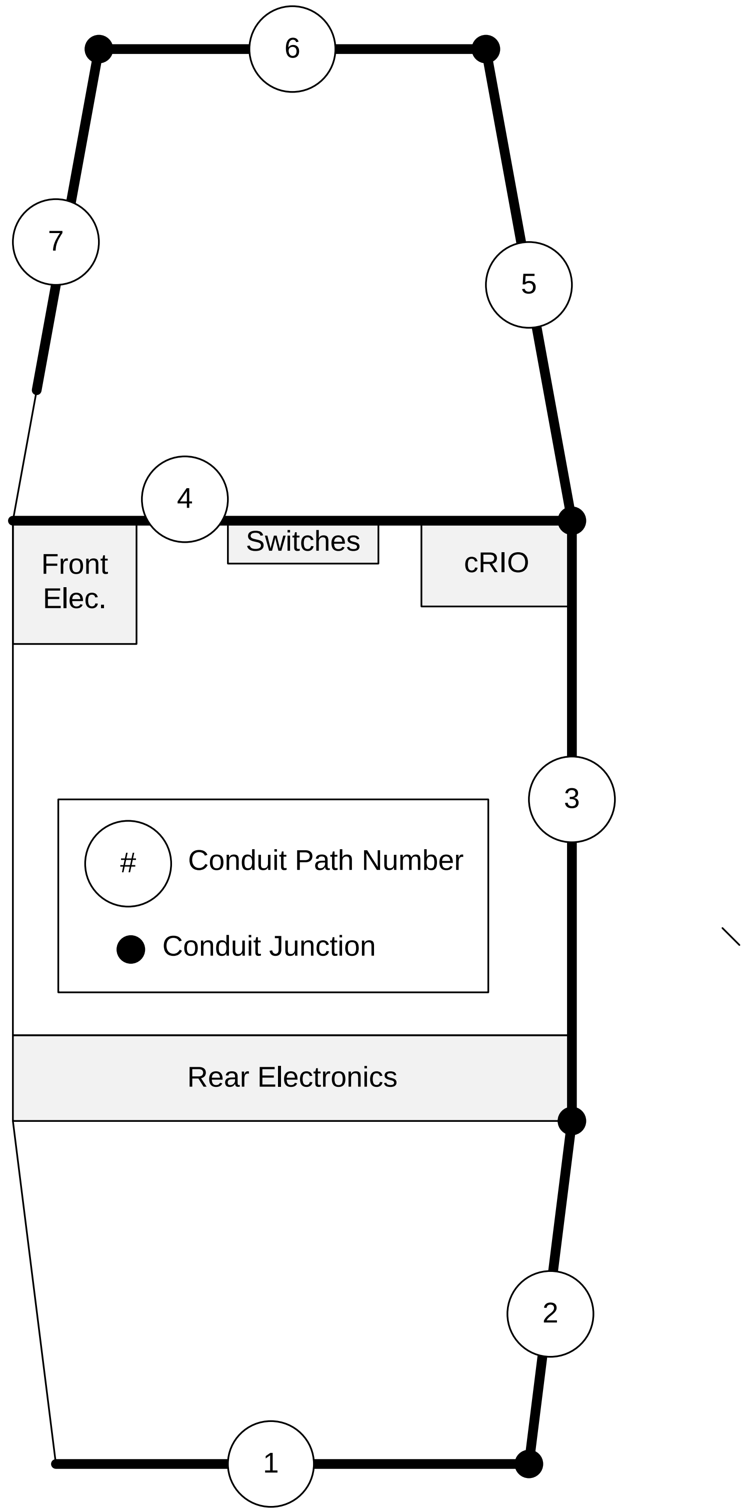
26 Charger Interface {17}
- 1 Plug(s) inserted in [A-20-8]
- 2 Switch in [D-7-6]
- 3 Gnd
- 4 LED out [D-?-?]

8.9 Soft Start Connector Control Board Schematic



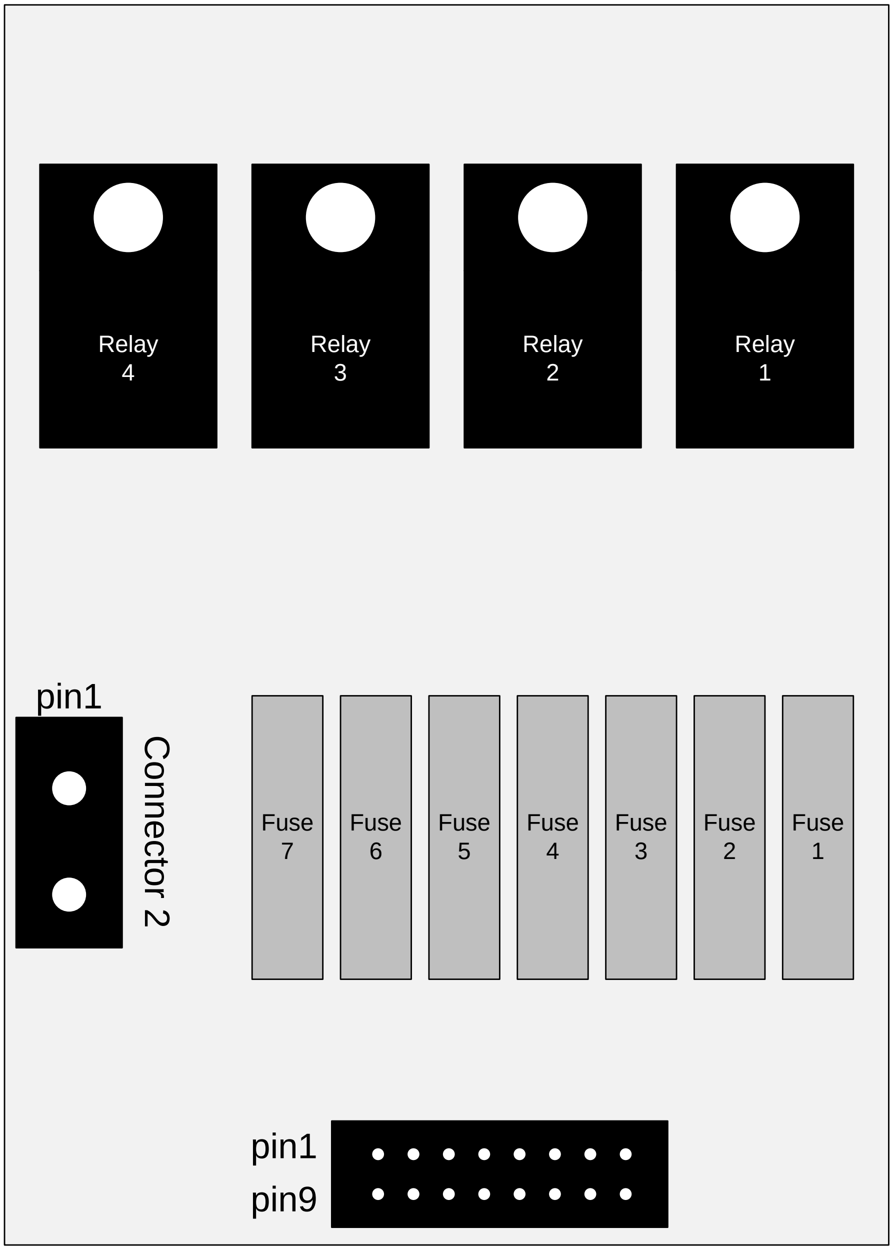
8.10 Car Wiring List

8.10.1 Car Wiring Harness Conduit Paths



Above is a diagram of the designated conduit paths used to route wires throughout the car. This diagram should be used with the wiring list to fix any damaged wire.

8.10.2 Diagram of Low Voltage Relay Enclosures



This diagram shows the connectors / fuses / and relays in the low voltage relay enclosures. This diagram should be combined with the following tables to replace fuses and diagnose potential problems.

8.10.3 Enclosure Pinouts and Wiring List

Front Relay Enclosure

Relay	Fuse	Connector #	Connector Pin	Wire Ref#	Description
-	1	1	8	99	UQM Pump
1	2	1	7	85	Rear defrost power
1	3	2	1	86	PTC power
2	4	1	16	82	Fan power
4	5	1	11	-	Engine off power
4	6	2	2	87	Engine power
4	7	1	9	100	EVO pump power
1	-	1	14	83	Heater on control
2	-	1	5	82	Fan on control
4	-	1	1	84	Engine power on control

Rear Relay Enclosure

Relay	Fuse	Connector #	Connector Pin	Wire Ref#	Description
1	1	1	8	67	TS
1	1	1	7	65	cRIO
1	2	1	6	101	DL1
1	2	1	5	101	Daq
1	2	1	4	102	DC/DC fan
1	3	-	-	-	Master board
1	3	1	1	103	Soft start
1	4	-	-	-	Batteries power
3	5	2	2	1	Aux power
-	6	1	12	68/63	Switch power 24/7
-	6	1	11	69	Radio power24/7
-	6	1	10	104	Daq 24/7
4	7	1	9	105	Rev lights
-	-	2	1	70	Brake booster
4	-	1	14	66	Reverse light on control
3	-	1	15	64	Auxiliary power on control
1	-	1	16	63	Generic LV power on control

Soft Start Enclosure

Connector Pin	Wire Color	Wire Ref#	Description
1	orange	57	Soft start power on (ground and + resistor)
2	black	56	Digital ground
3	yellow	58	Main Contactor power on (+ contactor)
4	green	59	Confirm main contactor closed
5	Pink	103	+12
6	blue	-	ground

8.10.4 Wiring List

ID#	Wire/Device Name	Paths	Min Gage	Wire Color	Start Point	End Point
	ACC Box, Rear					
1	12V Supply	--	8		Battery	Fuse Bus
2	AC Relay Gnd	3,4	22	white	Switches	2x AC Relays 85
3	Signal Flasher out	3,4	16	black	Flasher	Column Control black/red
4	Hazard Flahser out	3,4	16	green	Flasher	Switches
5	Brake Relay Gnd	3,4	22	white	Brake Switch	Brake Relay 85
6	A/C Compressor Power	2	10	red	A/C Relay 87	A/C Compressor In
7	A/C Blowers Power	2	10	red	A/C Relay 87	A/C Blowers In
8	Brake Relay Power L	2,1	20	yellow	Brake Relay 87	Left Brake Light
9	Brake Relay Power R	2	20	red	Brake Relay 87	Right Brake Light, Center Brake Light
10	Backup Cam Power	2,1	20	pink	Fuse Panel	Backup Camera Power in
11	**ACC Box, Front**					
12	12V Supply	3,4	10	red	DC/DC	Fuse Bus
13	Horn Relay Gnd	4	22	white	Switches	Horn Relay 85
14	Horn Power	4,5,6	16	green	Horn Relay	Horn x2
15	Defroster Relay Gnd	4	22	white	Switches	Defroster Relay 85
16	Defroster Power	4	14	white	Defroster Relay 87	Defroster Power in
17	Hi Beam Relay Gnd	4	22	white	Column Ctrl Red/Blue	Hi Beam Relay 85
18	High Beam Power	4,5,6	14	red	Hi Beam Relay 87	L,R Headlight
19	Low Beam Relay Gnd	4	22	white	Column Ctl Blue/Red	Lo Beam Relay 85
20	Low Beam Power	4,5,6	14	white	Lo Beam Relay 87	L,R Headlight
21	Parking Light Relay Gnd	4	22	white	Column Control Blue	Parking Relay 85
22	Parking Light Power, Front	4,5,6	18	light green	Parking Relay 87	Front L,R Headlight
23	Parking Light Power, Rear	4,3, 2,1	18	light green	Parking Relay 87	Rear Running Lights, License Plate
24	Radio Power	4	20	pink	Radio Fuse	Radio Red or Yellow?
25	Window Power	4	14	red/	Window Fuse	Left Window Green/White, Right Window Green/Black

				white		
26	Wiper Power	3,4	16	green	Wiper Fuse	Wiper Harness Green/Black, Column Control Green/Black
27	**Wiper Column Control**					
28	Wiper Power	--	16	green	Green/Black	Wiper Fuse,
29	Wiper Hi	4,5, 6,7	16	green	Blue/Yellow	Wiper Harness Blue/Yellow
30	Wiper Lo	4,5, 6,7	16	green	Blue	Wiper Harness Blue
31	Wiper Ground	--			Black	Chassis
32	**Wiper Harness**					
33	Wiper Gnd	--			Black	Chassis
34	Wiper Power	4,5, 6,7			Green/Black	Wiper Fuse
35	Wiper Hi	4,5, 6,7			Blue/Yellow	Column Control Blue Yellow
36	Wiper Lo	4,5, 6,7			Blue	Column Control Blue
37	Lighting Column Control					
38	Left Signal Power Front	4,5,6	18	light green	Green/Red	Left Front Signal, Left Indicator
39	Left Signal Power Rear	1,2, 3,4	18	light green	Green/Red	Left Rear Signal Red
40	Right Signal Front	4,5	18	light green	Green/Yellow	Right Front Signal, Right Indicator
41	Right Signal Power Rear	2,3,4	18	light green	Green/Yellow	Right Rear Signal Red
42	Signal Power Input	3,4	16	green	Black/Red	Signal Flasher
43	Column Ground	--	16		Black	Chassis
44	Hi Beam Ground	--			Red/Blue	Hi Beam Relay 85
45	Lo Beam Gnd	--			Blue/Red	Lo Beam Relay 85
46	Parking Gnd	--			Blue	Parking Relay 85
47	**Rear DC/DC**					

48	ground	3	24	black	DC/DC1	cRIO
49	enable	3	24	orange	DC/DC1	cRIO
50	status ok	3	24	green	DC/DC1	cRIO
51	**GFD**					
52	ground	3	24	blue	GFI	cRIO
53	+5	3	24	red	GFI	cRIO
54	analog resistance sig	3	24	green	GFI	cRIO
55	**SoftStart**					
56	ground	3	24	black	SS	cRIO
57	relay1 enable (soft start)	3	24	orange	SS	cRIO
58	relay2 enable (main)	3	24	yellow	SS	cRIO
59	OK	3	24	green	SS	cRIO
60	**Master**					
61	CAN	3	8	black	Master	cRIO
62	**Rear LV Relay**					
63	relay1 enable (through EDS)	4,3,2, 1,1,2	16	green	rear LV	cRIO
64	relay2 enable	3	22	white	rear LV	cRIO
66	relay3 enable rev	3	22	white	rear LV	cRIO
65	cRIO power	3	16	green	rear LV	cRIO
67	TS power	3,4	18	light green	rear LV	cRIO
68	switch power 24/7 (through EDS)	3,4	16	green	rear LV	cRIO
69	radio power 24/7	3,4	20	pink	rear LV	cRIO
70	brake booster	3	8	red	rear LV	booster
72	**Hall Effect**					
73	+24	3	24	red	hall eff	cRIO
74	ground	3	24	black	hall eff	cRIO
75	analog voltage	3	24	green	hall eff	cRIO

76	**Charger Interface Bx**					
77	wire1	3	24	red	chg box	cRIO
78	wire2	3	24	black	chg box	cRIO
79	wire3	3	24	green	chg box	cRIO
80	wire4	3	24	blue	chg box	cRIO
81	**Front Relay Box**					
82	Relay ctrl (fan)	5	22	white	front LV	cRIO
83	Relay ctrl(PTC/ defrost)	5	22	white	front LV	switch panel
84	Relay ctrl(engine)	4,5	22	white	front LV	switch panel
85	rear defrost power	3,5	14	red	front LV	rear window
86	PTC power	4,5	14	white	front LV	front window
87	Engine power	5	14	white	front LV	eng harness
88	**Front DC/DC**					
89	ground1	4,4	24	black	DC/DC1	cRIO
90	enable1	4,4	24	orange	DC/DC1	cRIO
91	status ok1	4,4	24	green	DC/DC1	cRIO
92	ground2	4,4	24	black	DC/DC1	cRIO
93	enable2	4,4	24	orange	DC/DC1	cRIO
94	status ok2	4,4	24	green	DC/DC1	cRIO
95	**UQM**					
96	CAN cable	5,6	8	black	cRIO	UQM
97	power +	5,6	22	pink	cRIO	UQM
98	power -	5,6	22	blue	cRIO	UQM
	Misc					
99	UQM pump	5,6	16		front relay box	uqm pump
100	EVO pump	5,6	16		front relay box	evo pump
101	Daq power	--	20		rear relay box	daq
102	DC/DC fan	--	22	white	rear relay box	DC/DC fan
103	Soft Start Power	--	20		rear relay box	Soft Start box
104	daq 24/7 power	--	20			
105	reverse light power	2,1	16		rear relay box	reverse light

8.10.5 cRIO IO module Pin Assignments

Analog Output		
Pin	**FPGA name**	**Assignment**
1	AI0	
2	AI1	**Accelerator Pedal 1**
3	AI2	**Accelerator Pedal 2**
4	AI3	**Brake Pedal**
5	AI4	Hall Effect (LV)
6	AI5	**Hall Effect (HV)**
7	AI6	**LV battery monitor**
8	AI7	**GFI sensor in**
9	DO0	
10	COM	Analog reference ground
11	AI16	**Genset Speed Information**
12	AI17	**Genset state (auto/force on)**
13	AI18	**FNR analog input**
14	AI19	
15	AI20	
16	AI21	
17	AI22	
18	AI23	
19	AISENSE	Analog Ref ground, tied to COM
20	AI8	**chg plugs in**
21	AI9	
22	AI10	
23	AI11	
24	AI12	
25	AI13	
26	AI14	
27	AI15	
28	PFIO	
29	COM	Analog reference ground
30	AI24	
31	AI25	
32	AI26	
33	AI27	
34	AI28	
35	AI29	
36	AI30	
37	AI31	

Digital Output/Input		
Pin	**FPGA name**	**Assignment**
1	DIO0	
2	DIO1	
3	DIO2	
4	DIO3	**High Voltage Relay Confirmed [I]**
5	DIO4	
6	DIO5	**Regen Enable Switch[I]**
7	DIO6	charge [I]
8	DIO7	**Turn High Voltage On Switch[I]**
9	COM	Digital common ground
10	COM	Digital common ground
11	DIO8	**Forward switch [I]**
12	DIO9	**Reverse switch [I]**
13	DIO10	**DC/DC 1 ok? [I]**
14	DIO11	**DC/DC 2 ok? [I]**
15	DIO12	**DC/DC 3 ok? [I]**
16	DIO13	
17	DIO14	EVO status[I]
18	DIO15	Engine Request Radiator fan [I]
19	RSVD	Reserved (no connection)
20	DIO16	**DC/DC 1 enabled [O]**
21	DIO17	**DC/DC 2 enabled [O]**
22	DIO18	**DC/DC 3 enabled [O]**
23	DIO19	**Radiator Fan Enable [O]**
24	DIO20	Engine Throttle Trigger [O]
25	DIO21	**Engine Ignition On/Off, EVO en, pump EN[O]**
26	DIO22	
27	DIO23	
28	COM	Digital common ground
29	COM	Digital common ground
30	DIO24	**Soft Start relay enable [O]**
31	DIO25	**High Voltage relay enable [O]**
32	DIO26	HV led control
33	DIO27	Charger Led Control
34	DIO28	
35	DIO29	
36	DIO30	
37	DIO31	

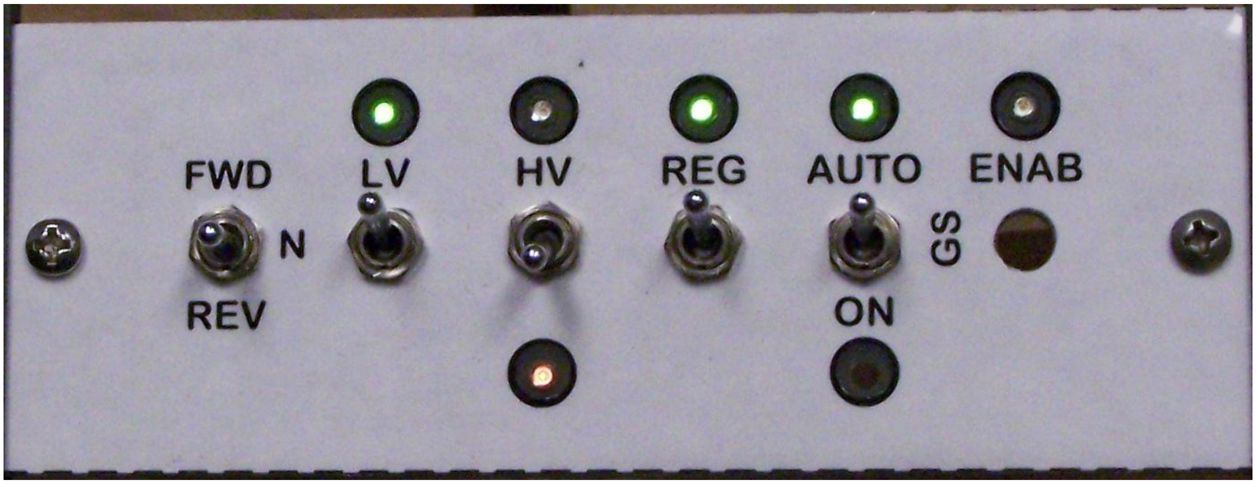
8.11 Data Log Excerpt

(03-24-10) Time(s/4)	BattV	BattSOC	BattTMax	BattErr	uqmSpeed	uqmV	uqmC	uqmTq	uqmTMax
289010	53.1	99	17.7	4448323232	1380.5	316.3	0	-0.7	39
289011	53.2	99	17.7	4448323232	1394	316.1	0	-1.1	39
289012	53.2	99	17.7	4448323232	1388	316.2	-0.4	-1.8	39
289013	53.2	99	17.7	4448323232	1377	316.3	-0.1	-1.1	39
289014	53.2	99	17.7	4448323232	1420	316.2	-0.2	-1.6	39
289015	53.2	99	17.7	4448323232	1386.5	316.2	-0.4	-1.6	39
289016	53.2	99	17.7	4448323232	1420.5	316.2	-0.4	-1.3	39
289017	53.2	99	17.7	4448323232	1463.5	316.3	2	1.7	39
289018	53.2	99	17.7	4448323232	1450	315.9	1.4	2.3	39
289019	53.2	99	17.7	4448323232	1450.5	315.8	3.9	5.7	39
289020	53.2	99	17.7	4448323232	1462.5	314.8	10.4	18.5	39
289021	53.2	99	17.7	4448323232	1473.5	314.4	11.1	21	39
289022	53.2	99	17.7	4448323232	1490.5	313.8	15.9	28.5	39
289023	53.2	99	17.7	4448323232	1502.5	313.9	12	22.3	39
289024	53.2	99	17.7	4448323232	1494	314.8	7.1	12.7	39
289025	53.2	99	17.7	4448323232	1447	316	-0.7	-1.7	39
289026	53.2	99	17.7	4448323232	1534	316	-0.1	-0.4	39
289027	52.8	99	17.7	4448323232	1542.5	313	21.7	38.6	39
289028	52.8	99	17.7	4448323232	1567	312.7	22.5	38.3	40
289029	52.8	99	17.7	4448323232	1573	311.8	28.2	48.6	40
289030	52.8	99	17.7	4448323232	1598	310.5	32.7	56.3	40
289031	53.2	99	17.7	4448323232	1618	310.3	34.6	58.2	40
289033	53.2	99	17.7	4448323232	1663.5	310.1	33.8	55.8	42
289034	53.2	99	17.7	4448323232	1692	309.9	34.1	55.5	42
289035	53.2	99	17.7	4448323232	1719	309.8	34.6	54.6	42

289036	53.2	99	17.7	4448323232	1765	309.6	37.1	56.6	42
289037	53.2	99	17.7	4448323232	1777	309.7	35.2	54	41
289038	53.2	99	17.7	4448323232	1796	309.4	34	52.4	41
289039	53.2	99	17.7	4448323232	1833.5	309.7	31.3	47.3	41
289040	52.2	99	17.7	4448323232	1859.5	309.8	31.8	47.1	41
289041	52.2	99	17.7	4448323232	1883	309.7	32.2	46.4	41
289042	52.2	99	17.7	4448323232	1906	310	29.7	42.6	41
289043	52.2	99	17.7	4048323232	1918	309.6	30.8	43.6	41
289044	52.2	99	17.7	4048323232	1932	311.5	16.4	23.2	41
289045	52.2	99	17.7	4048323232	1930	311.9	12	18.4	40
289046	52.2	99	17.7	4048323232	1959.5	311.8	19.1	27.6	40
289047	52.2	99	17.7	4048323232	1961	311.2	21.1	30.4	40
289048	52.2	99	17.7	4048323232	1985	311.6	19.6	27.7	40
289049	52.2	99	17.7	4048323232	1985.5	311.4	17.1	23.4	40
289050	52.2	99	17.7	4048323232	1999.5	311.7	19.8	27.5	40
289051	52.2	99	17.7	4048323232	2013.5	312.2	13.5	19.5	40
289052	52.2	99	17.7	4048323232	2027.5	312.2	12.5	16.1	40
289053	52.2	99	17.7	4048323232	2020	312.9	10	14.1	40
289054	52.2	99	17.7	4048323232	2045	312.8	9.9	13	40
289055	52.2	99	17.7	4032323232	2045	313.3	9.3	13.2	40
289056	52.5	99	17.7	4032323232	2037	314.1	8.2	6.9	40
289057	52.5	99	17.7	4032323232	2041	313.5	6.4	9.6	41
289058	52.5	99	17.7	4032323232	2043.5	314.6	-0.8	-0.6	41

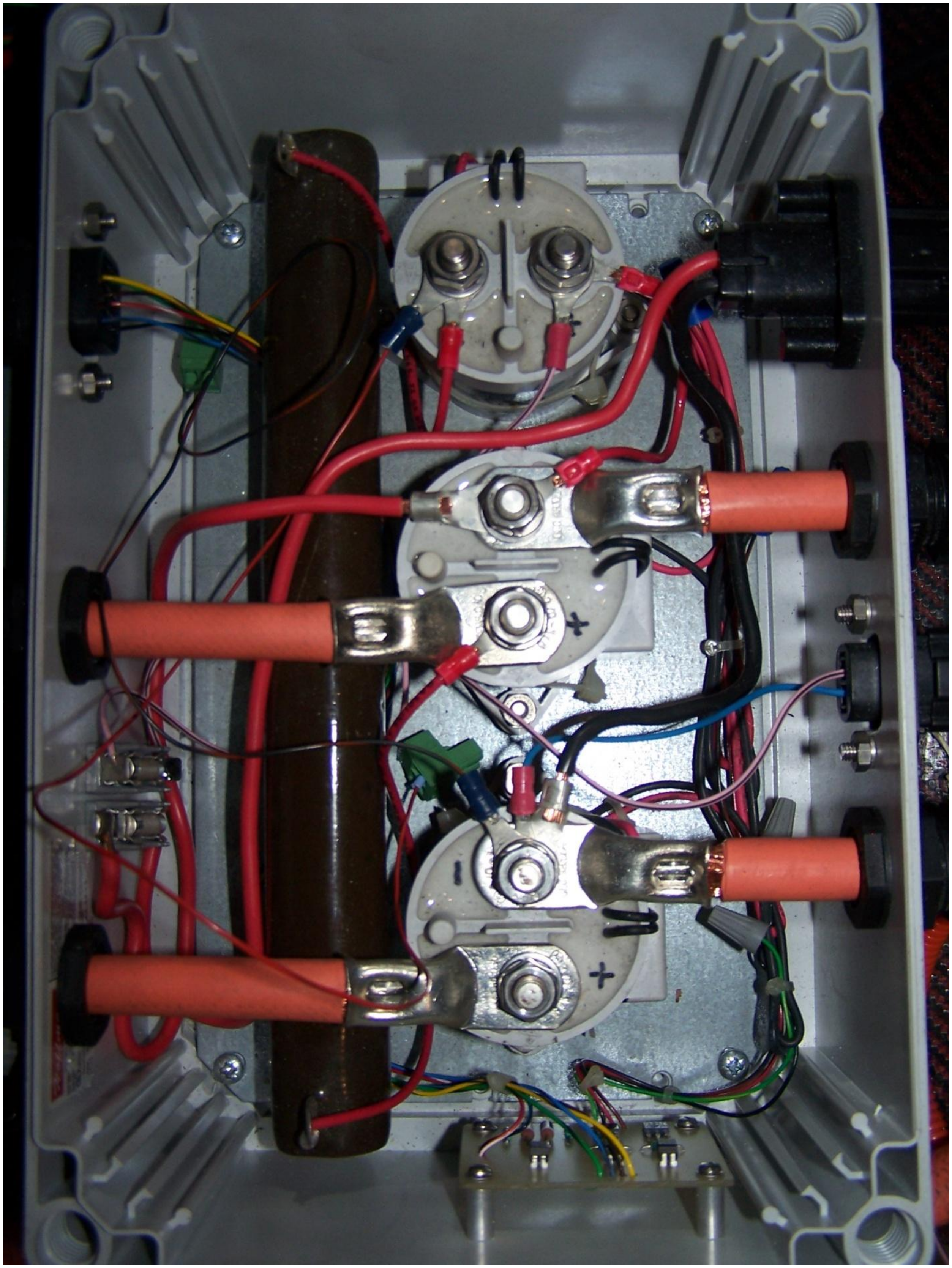
8.12 Selected Pictures of Electrical Enclosures

8.12.1 Lit Switch Panel

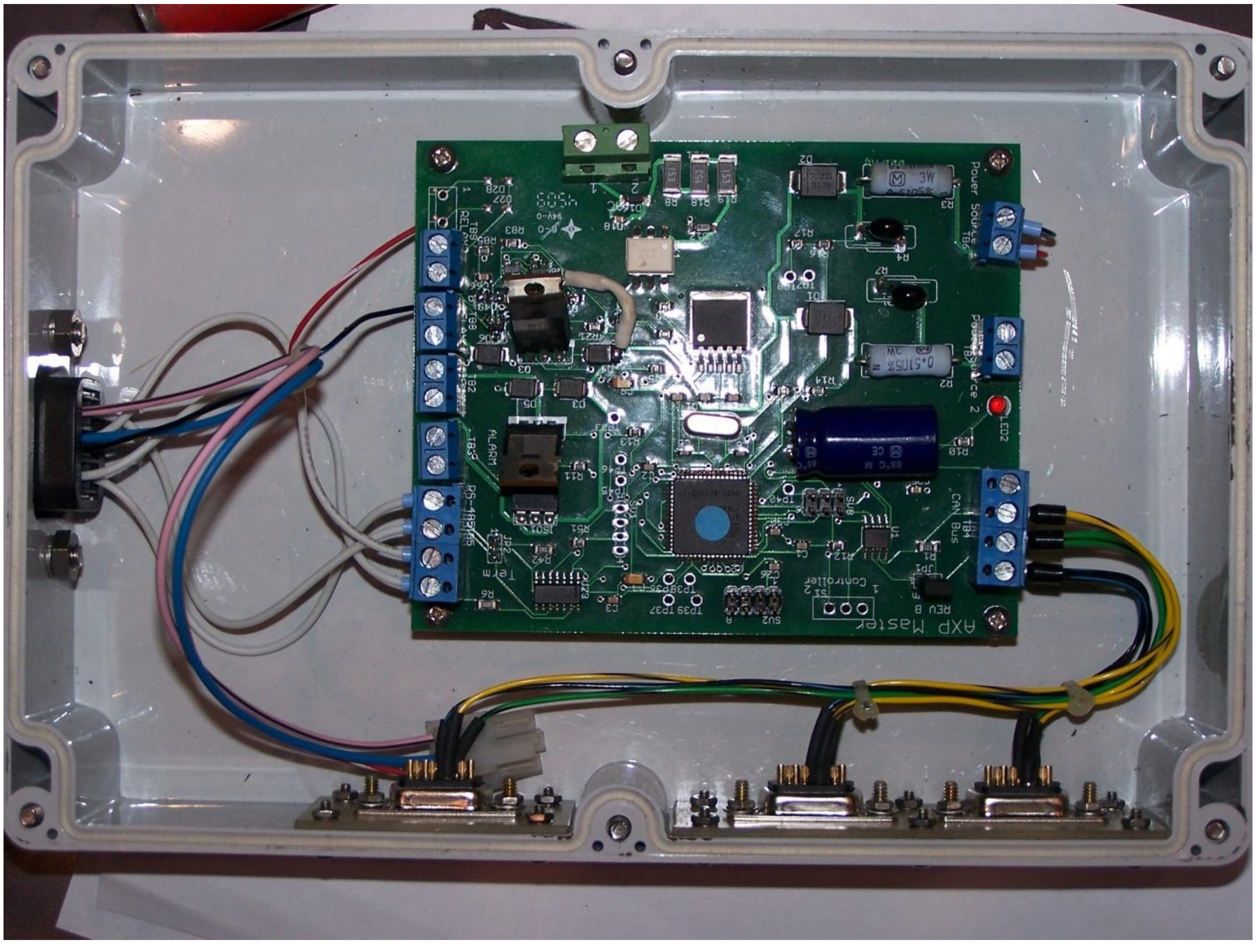


8.12.2 Soft Start Enclosure Lid with GFD and Interface Board

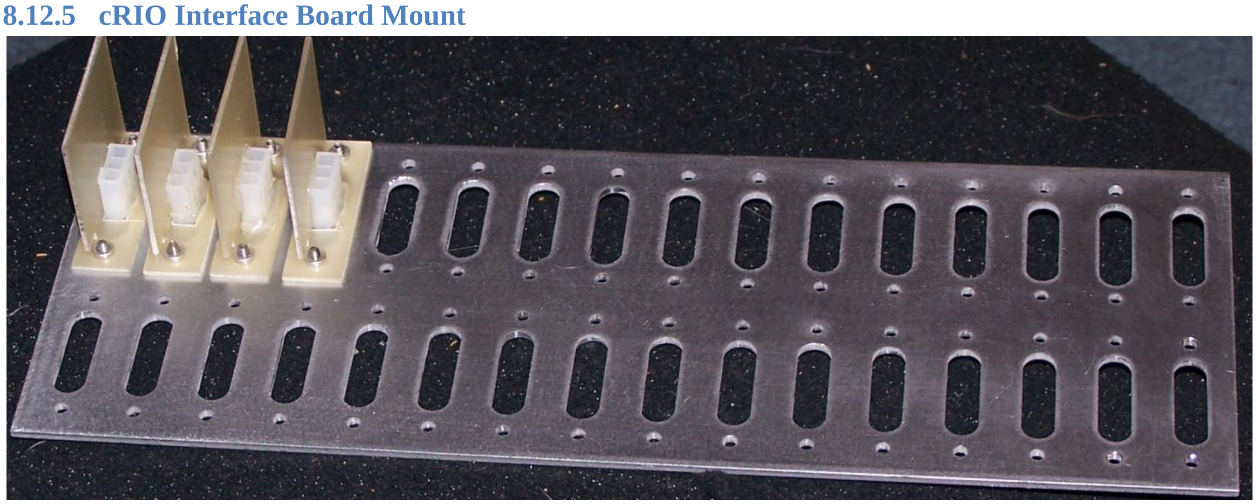
8.12.3 Soft Start Enclosure



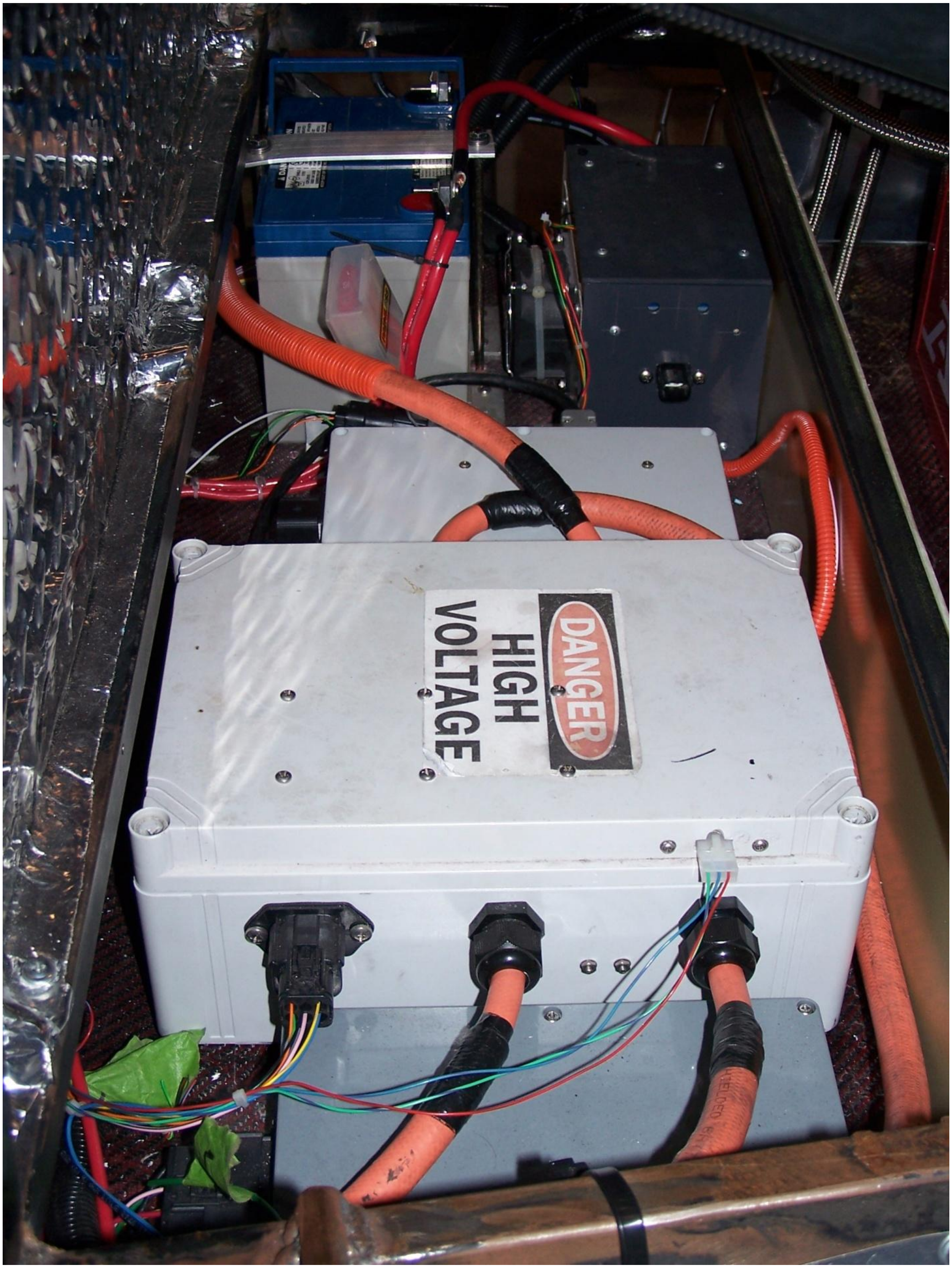
8.12.4 Rear Low Voltage Relay Lid with Master Board



8.12.5 cRIO Interface Board Mount



8.12.6 Rear Electronics Bay



8.13 Manufacturer Spec Sheets

(Relevant Specification Sheets are reproduced on the following pages in full)

PowerPhase® 125

for electric, hybrid electric, and fuel cell powered vehicles

Key Features:

- 300 Nm peak torque
- 125 kW peak, 45 kW continuous motor power
- 125 kW peak, 41 kW continuous generator power
- Full Power at 300-420VDC
- EV/HEV traction drive or HEV starter/generator system
- Efficient, power dense, brushless permanent magnet motor
- Microprocessor-controlled inverter with sine wave drive
- Application-friendly graphical user interface
- Regenerative Braking

Driver Electronics Incorporate:

Serial communication

CAN bus compatibility

Diagnostic capability

Temperature sensing/alarm

Speed sensing

Graphical user interface

Benefits:

Tight voltage regulation

Improved braking and extended range

Suitable for automotive applications

Enhanced thermal management

Torque, speed, and voltage control modes

Rugged, weatherproof enclosure

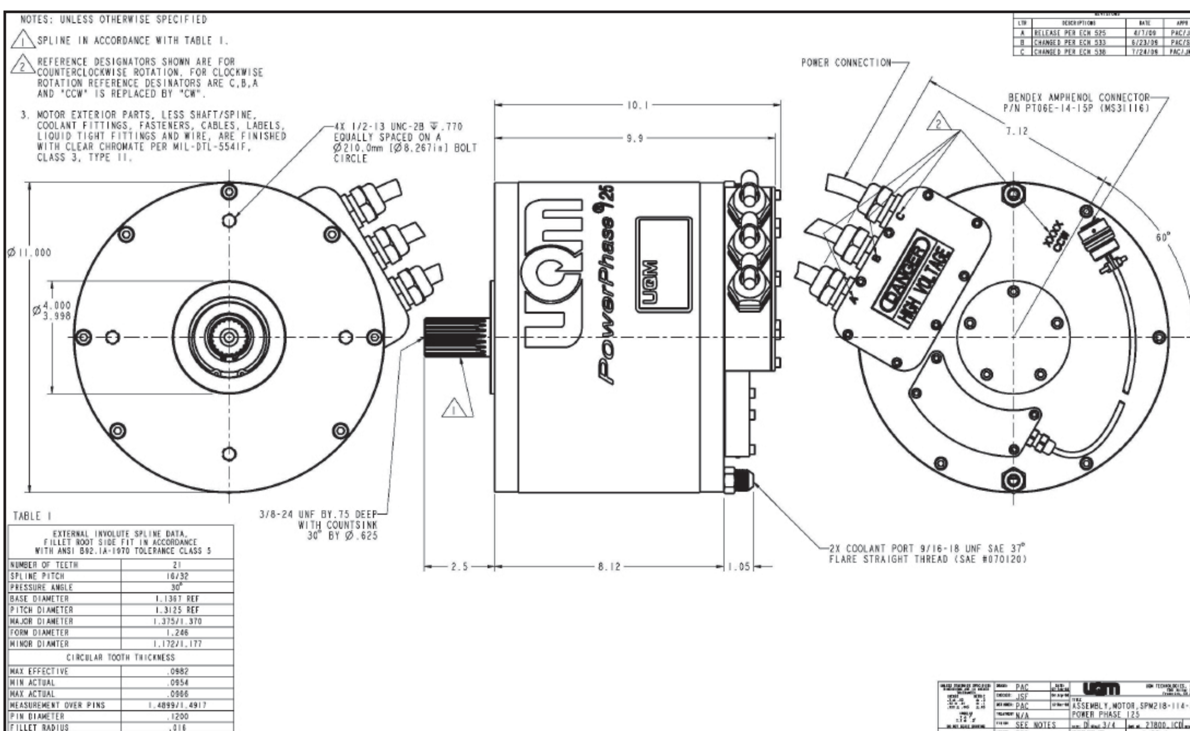
Liquid cooling

Light weight

PowerPhase® 125

HPM125 Motor/Generator

Dimensions		
Length	9.94 in	252 mm
Diameter	11.00 in	280 mm
Weight	90 lb	41 kg
Performance		
Peak power	167 hp	125 kW
Continuous power at 3,000 rpms	60 hp	45 kW
Peak torque	221 lbf•ft	300 N•m
Continuous torque	110 lbf•ft	150 N•m
Maximum speed	8000 RPM	
Maximum efficiency	94%	
Power density (based on 50 kW)	1.85 hp/lb	3.05 kW/kg



www.uqm.com sales@uqm.com 303.278.2002 7501 miller dr., frederick CO 80530

PowerPhase® 125

DD45-500L Inverter/Controller

Operating Voltage

Nominal input range	300 to 420 VDC
Operating voltage input range	240 to 420 VDC
Minimum voltage limit	240 VDC *(with derated power output)*
Input current limitation	500 A

Dimensions

Length	14.96 in	380 mm
Width	14.37 in	365 mm
Height	4.69 in	119 mm
Weight	35.0 lb	15.9 kg

Inverter Type

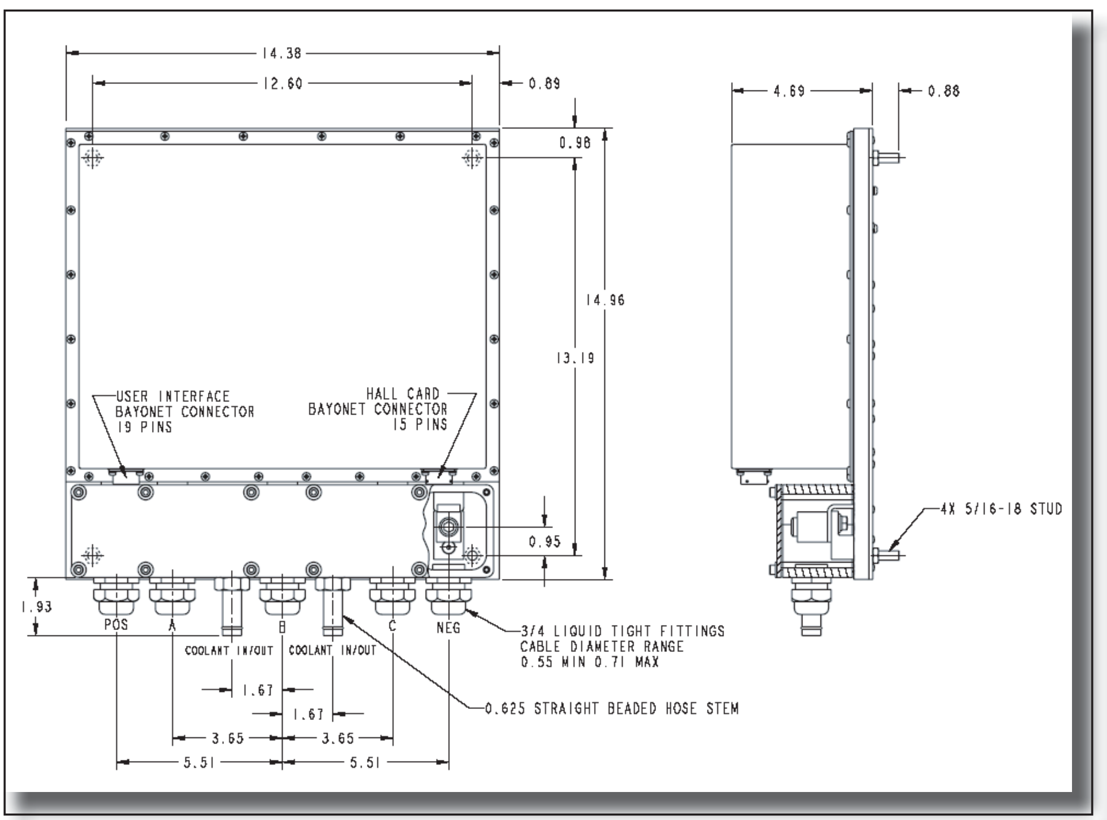
Control type	PWM & phase advance,
	3-Phase Brushless PM
Power device	IGBT module half bridge × 3
Switching frequency	12.5 kHz
Standby power consumption	17 W *(inverter and microprocessor)*

Liquid Cooling System

Minimum coolant flow 8 l/min *(50/50 water/glycol mix)*		
Max. inlet temp of controller	131° F	55° C
Inner diameter of hose	5/8 in	16 mm
Max. inlet pressure	10 psig	0.7 bar

TI2812 Digital Signal Processor (internally packaged)

Nominal input voltage	12 VDC
Input supply voltage range	8 to 15 VDC
Input supply current range	0.3 to 0.5 A



REKEB115 Specification Summary
EVO Electric Ltd

Document Summary

Date:	12/01/2010
Issued Revision:	Draft
Distribution:	EVO Electric Ltd

EVO Electric Ltd.Unit 14 Woking Business Park, Woking, Surrey, GU21 5JY
Tel: +44 (0) 1483 745010 Fax: +44 (0) 1483 770506

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1. Introduction and Scope 2
2. I/O Connections 4
2.1 Control connector 4
2.2 Motor connector 6

1. Introduction and Scope

The REKEB115 is an inverter designed to control an Evo Axial Flux Permanent Magnet Synchronous Motor (PMSM). External views of these units are shown in Figure 1.

REKEB115-320

AF140 motor

Fig. 1. Example drive system offered by EVO Electric Ltd

A summary specification of the inverter is listed in Table 2.

Designation	REKEB 115
Nominal voltage	320 V_{DC}
Operational voltage range	290– 450 V_{DC}
Rated output current	115 A_{AC}
Peak output current (30sec)	172 A_{AC}
Continuous Power	33 kW
Maximum Power	48 kW
Peak efficiency	98%
Control scheme	Closed loop vector control

EVO Electric Ltd.Unit 14 Woking Business Park, Woking, Surrey, GU21 5JY
Tel: +44 (0) 1483 745010 Fax: +44 (0) 1483 770506

Motor position sensor	Resolver
Coolant	50/50 water/glycol mix
Coolant flow rate	8.0 Litres/minute
Maximum coolant inlet temperature	55 ℃
Coolant connections	½" BSP
Operational ambient Temperature	-10℃ to +40℃
Weight	24 kg

Table 1 REKEB115 inverter specification

A drive system comprised of an AFM140-3 motor and a REKEB115 inverter typically achieves the following performance values.

Continuous Torque	145 Nm
Peak Torque	215 Nm
Base speed[1]	2400rpm
Maximum speed[1]	3200rpm
Nominal power	36kW
Peak Power	48kW

Table 2 Drive system summary specification

<u>Note</u>
[1]: At a nominal DC bus voltage of 320V

EVO Electric Ltd.Unit 14 Woking Business Park, Woking, Surrey, GU21 5JY
Tel: +44 (0) 1483 745010 Fax: +44 (0) 1483 770506

Technical Sales
United States
(866) 531-6285
info@ni.com

Requirements and Compatibility | Ordering Information | Detailed Specifications | Pinouts/Front Panel Connections
For user manuals and dimensional drawings, visit the product page resources tab on ni.com.

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CompactRIO Integrated Systems with Real-Time Controller and Reconfigurable Chassis

NI cRIO-907x

- Integrated CompactRIO systems with a reconfigurable FPGA chassis and embedded real-time controller
- Lower-cost systems for high-volume OEM applications
- Up to 2M gate reconfigurable FPGA
- 8 slots for C Series I/O modules
- Up to 400 MHz real-time processor
- Up to 128 MB DRAM memory, 256 MB of nonvolatile storage
- Up to two 10/100BASE-TX Ethernet ports with built-in FTP/HTTP servers and LabVIEW remote panel Web server
- RS232 serial port for peripheral devices

Overview

NI cRIO-907x integrated systems combine an industrial real-time controller and reconfigurable field-programmable gate array (FPGA) chassis for high-volume and industrial machine control and monitoring applications. The new NI cRIO-9072 integrated system features an industrial 266 MHz real-time processor and an eight-slot chassis with an embedded, reconfigurable 1M gate FPGA chip. The new NI cRIO-9074 integrated system contains a 400 MHz real-time processor and an eight-slot chassis with an embedded, reconfigurable 2M gate FPGA chip. Both systems feature built-in nonvolatile memory and a fault tolerant file.

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Requirements and Compatibility

OS Information

- VxWorks

Driver Information

- NI-RIO

Software Compatibility

- LabVIEW
- LabVIEW Real-Time Module
- LabVIEW Professional Development System
- LabVIEW FPGA Module

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Comparison Tables

Product	Processor Speed (MHz)	FPGA Size (Gates)	Module Slots	DRAM (MB)	Internal Nonvolatile Storage (MB)	10/100BASE-T) Ethernet Port	RS232 Serial Port	Power Supply Input Range	Remote Panel Web and FTP Server
NI cRIO-9072	266	1 M	8	64	128	yes	yes	19 to 30 VDC	yes
NI cRIO-9073	266	2 M	8	64	128	yes	yes	19 to 30 VDC	yes
NI cRIO-9074	400	2 M	8	128	256	yes (Dual)	yes	19 to 30 VDC	yes

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Application and Technology

System Configuration

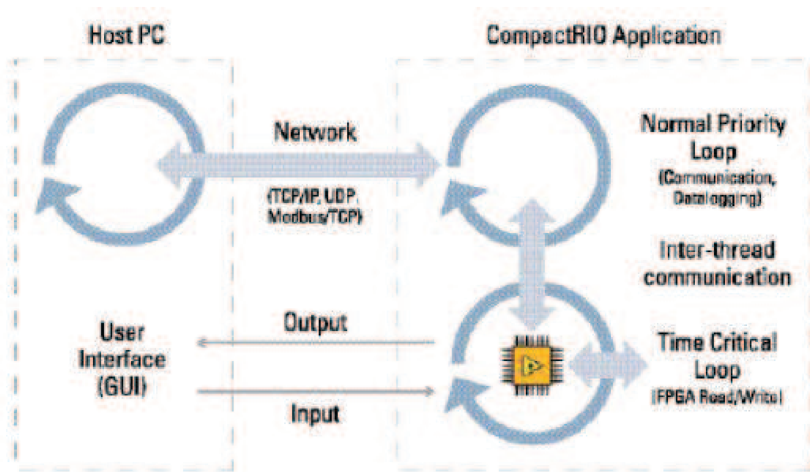
These NI CompactRIO real-time controllers connect to any four- or eight-slot CompactRIO reconfigurable chassis. The user-defined FPGA circuitry in the chassis controls each I/O module and passes data to the controller through a local PCI bus using built-in communication functions.

These systems also accept up to eight NI C Series I/O modules. A variety of I/O modules are available including voltage, current, thermocouple, RTD, accelerometer, and strain gage inputs; up to ±60 V simultaneous sampling analog I/O; 12, 24, and 48 V industrial digital I/O; 5 V/TTL digital I/O; counter/timers; pulse generation; and high voltage/current relays.

The 10/100 Mbits/s Ethernet port allows for programmatic communication over the network and built-in Web (HTTP) and file (FTP) servers. The cRIO-9074 features dual Ethernet ports, which allows for the use of one port for network communication to a host PC or enterprise system and the other port for expansion I/O (easily connect another CompactRIO system or another Ethernet-based device for additional I/O).

Embedded Software

You can synchronize embedded code execution to an FPGA-generated interrupt request (IRQ) or an internal millisecond real-time clock source. The LabVIEW Real-Time ETS OS provides reliability and simplifies the development of complete embedded applications that include time-critical control and acquisition loops in addition to lower-priority loops for postprocessing, data logging, and Ethernet/serial communication. Built-in elemental I/O functions such as the FPGA Read/Write function provide a communication interface to the highly optimized reconfigurable FPGA circuitry. Data values are read from the FPGA in integer format and are then converted to scaled engineering units in the controller.



CompactRIO Software Architecture

Built-In Servers

In addition to programmatic communication via TCP/IP, UDP, Modbus/TCP, IrDA, and serial protocols, the CompactRIO controllers include built-in servers for Virtual Instrument Software Architecture (VISA), HTTP, and FTP. The VISA server provides remote download and communication access to the reconfigurable I/O (RIO) FPGA over Ethernet. The HTTP server provides a Web browser user interface to HTML pages, files, and the user interface of embedded LabVIEW applications through a Web browser plug-in. The FTP server provides access to logged data or configuration files.

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Detailed Specifications

The following specifications are typical for the – 20 to 55 °C operating temperature range unless otherwise noted.

Network	
Network interface	10BaseT and 100BaseTX Ethernet
Compatibility	IEEE 802.3
Communication rates	10 Mbps, 100 Mbps, auto-negotiated
Maximum cabling distance	100 m/segment
RS-232 Serial Port	
Maximum baud rate	115,200 bps
Data bits	5, 6, 7, 8
Stop bits	1, 2
Parity	Odd, Even, Mark, Space
Flow control	RTS/CTS, XON/XOFF, DTR/DSR
SMB Connector (cRIO-9074 Only)	
Output Characteristics	
Minimum high-level output voltage	
With –100 µA output current	2.9 V
With –16 mA output current	2.4 V
With –24 mA output current	2.3 V
Maximum low-level output voltage	
With 100 µA output current	0.10 V
With 16 mA output current	0.40 V
With 24 mA output current	0.55 V
Driver type	CMOS
Maximum sink/source current	±24 mA
Maximum 3-state output leakage current	±5 µA
Input Characteristics	
Minimum input voltage	0 V
Minimum low-level input voltage	0.94 V
Maximum high-level input voltage	2.43 V
Maximum input voltage	5.5 V
Typical input capacitance	2.5 pF

Typical resistive strapping	1 kΩ to 3.3 V

Memory

cRIO-9072, cRIO-9073	
Nonvolatile	128 MB
System memory	64 MB
cRIO-9074	
Nonvolatile	256 MB
System memory	128 MB

Reconfigurable FPGA

cRIO-9072	
Number of logic cells	17,280
Available embedded RAM	432 kbits
cRIO-9073, cRIO-9074	
Number of logic cells	46,080
Available embedded RAM	720 kbits

Internal Real-Time Clock

Accuracy	200 ppm; 35 ppm at 25 °C

Power Requirements

Caution You must use a National Electric Code (NEC) UL Listed Class 2 power supply with the cRIO-9072/3/4.

Recommended power supply	48 W, 24 VDC
Power consumption	20 W maximum
Power supply input range	19 to 30 V

Physical Characteristics

If you need to clean the controller, wipe it with a dry towel.

Screw-terminal wiring	0.5 to 2.5 mm 2 (24 to 12 AWG) copper conductor wire with 10 mm (0.39 in.) of insulation stripped from the end
Torque for screw terminals	0.5 to 0.6 N · m (4.4 to 5.3 lb · in.)
Weight	929 g (32.7 oz)

Safety Voltages

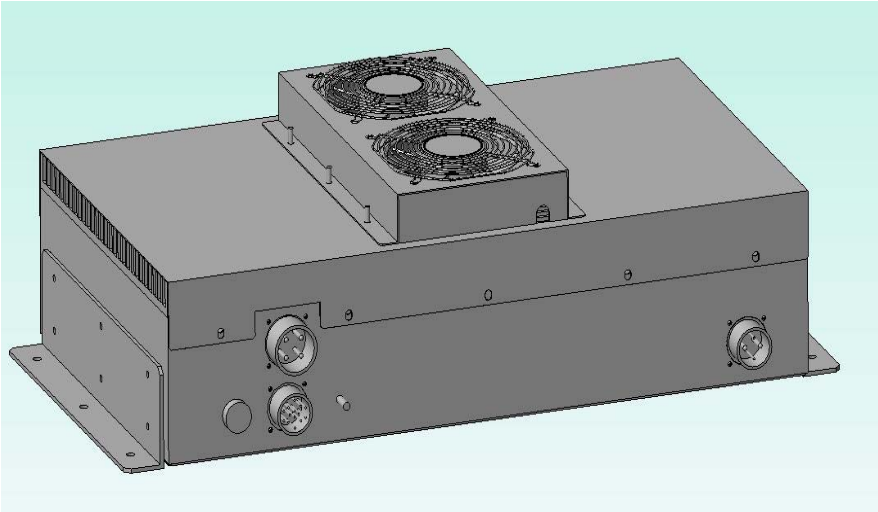
Connect only voltages that are within these limits.

V terminal to C terminal	35 V max, Measurement Category I

Measurement Category I is for measurements performed on circuits not directly connected to the electrical distribution system referred to as MAINS

CMP313 Series

7KW Sealed, Single-Phase, ON-BOARD Chargers for Lithium Battery Vehicles



APPLICATIONS

CMP313 charger series is a very Versatile, safe high-tech charger for high-end on-board electric vehicle applications.

CMP313 charger series can charge Lithium battery packs safely and powerfully.

FEATURES

- **HFPC (High Frequency Power Converter) topology.**
- **Fully CAN v2.0B controlled.**
- **High efficiency and high Input Power Factor**
- **AC/DC full off line isolation, this assures maximum personal protection.**
- **IP54 protection degree**
- **Outputs are short-circuit protected.**
- **Output reverse polarity is protected by internal fuse.**
- **Remote alarm.**

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Input Data		Units
Input Voltage Range (Single Phase)	192...276	Vac
Line Frequency	47...63	Hz
Maximum Input current @ 192Vac	41	Aac
Absorbed maximum Apparent Power	7900	VA
Power Factor	> 0.98	

General Data		Units
Protections	Output overvoltage Output overcurrent Output polarity reversal Input overvoltage	
Ambient Temperature	-20...+50	°C
Power derating	-5%/°C (from 40°C to 50°C)	
Heat Dissipation	IP54 FAN cooling	
Protection Degree	IP54	
Efficiency	> 90 @ at max load	%
Control interface	CAN v2.0B (500Kbit/s, standard frame, ID's adaptable)	
Remote alarm	N.C. contact potential free ("OR" of thermal protection, overvoltage, etc.)	
Mains presence	N.O. contact potential free (when the input mains is present the contact closes)	

Ouputs Data	CMP313-01	CMP313-02	Units
V01 Output Voltage (max)	294	392	Vdc
V01 Output Current (max)	23	18	Adc
V01 Rated Output Power	7000		W
V01 Costant current control	by CAN or by PWM (isolated)		
V02 Output BMS Voltage	12		Vdc
V02 Output BMS Current	0,1		Adc
V03 Output FAN Voltage	24		Vdc
V03 Output FAN Current	1,0		Adc

Standard Applied		Units
General Requirements	EN 61851-1, EN 61851-21	
EMC – Emission	EN61000-3-4, CISPR 14, 16 level A	
EMC – Immunity	EN61000-4-1, EN61000-4-4, EN61000-4-5, EN61000-4-11, EN61000-4-3	
SAFETY	EN 60950-1:2002 + A11:2004, ECE regulation 100	
Dielectric Withstand Voltage	Input / PE: 2000Vac @ 1min. Input / Output: 2000Vac @ 1min. Output / PE: 1000Vdc @ 1min. Input / SELV: 4000Vac @ 1min.	
Insulation resistance	Input, Output / PE: > 1MΩ @ 500Vdc	
Touch current	< 3.5	mA

Mechanical Data		Units
Dimensions: Width x Depth x Height	616 x 304 x 176,5	mm
Weight (ca.)	23	Kg
Case Material	Aluminium / Steel (black cataphoresis painted)	
Case Type	Box	
I/O Connections	Input (1L + N + PE + Pilot): IP67 MS Circular connectors Power Output (to battery packs): IP67 MS Circular connectors Control signal and Interface: IP67 MS Circular connectors	

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TDK·Lambda

PAF-F280 Series

200V to 400VDC Input Full brick DC-DC Converters

- Output Voltages from 7.2V to 57V
- 450W to 600W Output Power
- Current Share
- Operation to 100°C Baseplate
- Wide Adjustable Output Range

RoHS

Key Market Segments & Applications

Servers & Rail Systems
High End Computers
Custom Power Supplies

PAF Features and Benefits

Feature	Benefit
◆ Wide Adjustment Range	◆ Reduces need for custom modules
◆ Parallel Pin	◆ Modules can be connected together for higher current
◆ High Efficiency - up to 91%	◆ Reduced heat losses

Specifications

ITEMS / MODEL		PAF450F280-12 PAF600F280-12	PAF450F280-24 PAF600F280-24	PAF450F280-28 PAF600F280-28	PAF450F280-48 PAF600F280-48
Nominal Output Voltage	VDC	12	24	28	48
Output Current (Max) 450W	A	38	19	16.5	9.5
600W		50	25	21.5	12.5
Max Output Power 450W	W	456	456	462	456
600W		600	600	602	600
Efficiency (Typ)	%	89-90	91	91	91
Input Voltage Range	VDC	200-400VDC			
Output Voltage Accuracy	%	±1			
Output Voltage Adjustment	VDC	7.2 - 14.4	14.4 - 28.8	16.8 - 33.6	28.8 - 57.6
Max Ripple & Noise	mV	120	240	280	480
Max Line Regulation	mV	48	56	56	96
Max Load Regulation	mV	48	56	56	96
Temperature Coefficient	°C	0.02%/°C			
Overcurrent Protection	%	105 - 140%			
Overvoltage Protection	%	125 - 145%			
Signals & Control	-	Remote Sense, Remote On/Off, Parallel Pin, Inverter Good, 11-14V Auxiliary voltage			
Baseplate Temperature	-	-40°C to +100°C Baseplate: (See derating chart)			
Humidity (non condensing)	-	5 - 95% RH Operating, 5 - 95% RH Non Operating			
Cooling	-	Conduction (See Installation Manual for heatsink selection)			
Isolation Voltage	-	Input to Baseplate: 2500VAC (20mA); Input to Output 3000VAC for 1 min.; Output to Baseplate: 500VDC for 1 min			
Shock	-	196.1m/s^2			
Vibration	-	Non Operating, 10-55Hz (sweep for 1 min.) Amplitude 0.825mm constant (Max 49 m/s^2) X,Y,Z 1 hour each			
Safety Agency Approvals	-	UL60950-1, CSA60950-1, EN60950-1, CE LVD			
Weight (Typ)	g	200			
Size (WxHxD)	mm	2.4 x 0.5 x 4.6 (61 x 12.7 x 116.8) See outline drawing			
Warranty	yr	2 years			

Note: See Installation Manual for full details, test methods of parameters and application notes.