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DOE Award #DE-FC26-08NT02377
August 27, 2010

FINAL TECHNICAL REPORT

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Modular Energy Storage System for Hydrogen Fuel Cell Vehicles

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Executive Summary

The objective of the project is to develop technologies, specifically power electronics, energy storage electronics and controls that provide efficient and effective energy management between electrically powered devices in alternative energy vehicles – plug-in electric vehicles, hybrid vehicles, range extended vehicles, and hydrogen-based fuel cell vehicles. The in-depth research into the complex interactions between the lower and higher voltage systems from data obtained via modeling, bench testing and instrumented vehicle data will allow an optimum system to be developed from a performance, cost, weight and size perspective. The subsystems are designed for modularity so that they may be used with different propulsion and energy delivery systems. This approach will allow expansion into new alternative energy vehicle markets.

Initially, the goal was to develop an electrical vehicle environment ideal for fuel cell applications. The environment was extended to be flexible and modular so that other alternative energy sources could be used in place of a fuel cell, such as batteries and gensets. From a packaging and cost perspective, it is desired to minimize the size of the fuel cell which directly corresponds to a lower output voltage. The electric vehicle's traction motor is more efficient at higher voltages. A DC/DC converter is used to boost the system voltage of the fuel cell to a usable level for the traction motor to optimize the system. A high voltage energy storage system is employed to capture this energy to take advantage of regenerative braking. The energy storage system also provides transient power to the electric motor which allows the operating point of the fuel cell or other alternative energy sources to be optimized. A block diagram representing this system is shown in Figure 1.

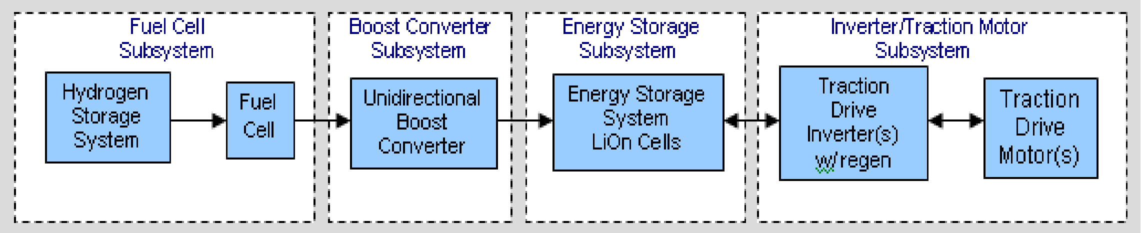

Figure 1. Energy Delivery, Conversion, Storage and Propulsion Systems

In conclusion, the results of the project were:

- Design and implementation of an energy storage system into a surrogate electric vehicle
- Energy storage system, DC/DC converter and alternative energy source requirements obtained from vehicle simulation with aggressive US06 vehicle drive cycle
    - Worse-case power output required by the inverter: 100 KW @ 400A max
    - Average vehicle power load (aggressive drive cycle w/ & w/o regeneration): 17 KW / 20 KW
    - High Voltage Operating Range: 240 – 350V
    - Fuel cell and DC/DC converter maximum output power: 30 KW
    - Fuel cell minimum voltage: 100V @ 300A max
- DC/DC boost converter design requirements and circuit development
    - Maximum Input Current: 330 A @ 100 V (110 A per phase)
    - Maximum Operating Voltage: 365 V
    - Switching Frequency: 22 kHz
    - Estimated Efficiency: Greater than 96%
    - Temperature Range: -40° C to 100° C

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1 Introduction

An electrical vehicle environment was established to promote research and technology development in the area of high power energy management. The project incorporates a topology that permits parallel development of an alternative energy delivery system and an energy storage system. The goal of the project is efficient and effective energy management between these systems. In order to meet the project objectives, the vehicle energy management system (VEMS) was defined and subsystem requirements were obtained. Next, power electronics, energy storage electronics and controls were designed. Finally, these subsystems were built and integrated into a surrogate electric vehicle to evaluate and optimize the subsystems performance. This project focused on defining subsystem requirements, design and construction of the energy management subsystem, and the integration of this subsystem into the surrogate electric vehicle. In addition, under the scope of the project, a boost converter that couples the alternate energy delivery system to the energy storage system was developed. Figure 2 illustrates the Vehicle Energy Management System.

Under the original project scope, an energy delivery system for hydrogen-based fuel cell applications was developed. However, the scope was expanded to include other alternative energy sources (i.e. batteries and gensets). Some of the major drawbacks of using fuel cell systems on vehicles are: (1) cost, (2) size and (3) a limited refueling infrastructure. Also, fuel cells are not able to accept regenerated energy from the electric vehicle's traction motor during deceleration (electrical braking). A lower voltage fuel cell system is used to offset some of the cost and size constraints – this means lower cost and smaller packaging. The system voltage is boosted by a DC/DC converter to a higher voltage range, and provides the traction motor the ability to operate at optimum power efficiency levels since by itself it cannot efficiently operate the traction motor. An energy storage system is used on the higher voltage side to capture regenerated energy from the motor. The energy storage system also provides the instantaneous power needed by the traction motor/inverter, as well as the flexibility for the alternative energy source to operate at stable and optimum operating points.

A Li-ion battery was used as the alternative energy which meant a reduction in cost, complexity and ultimately, timing. Under this project, the intent was to have the Li-ion battery of the alternative energy source to have similar electrical characteristics to that of the required fuel cell. This includes having similar voltage and current operating ranges, and equivalent response times to output power command levels.

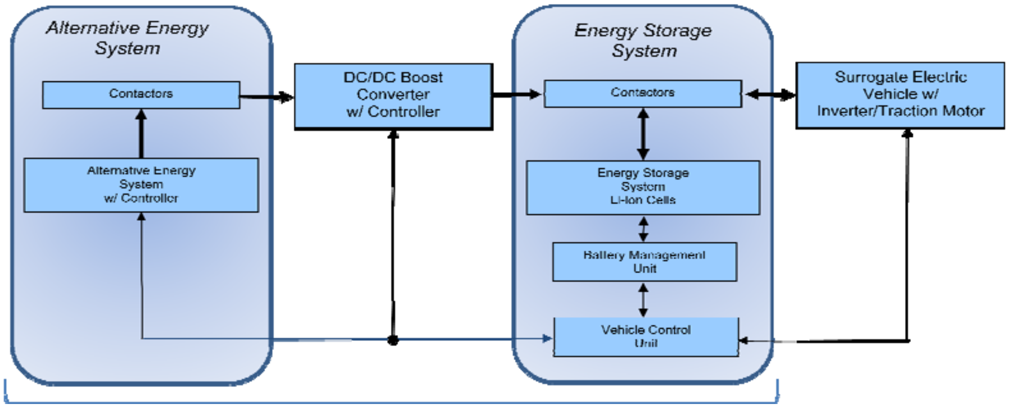

Figure 2. Vehicle Energy Management System – VEMS

2 Vehicle Energy Management Subsystem Requirements

Simulations were used extensively to develop the requirements of the energy storage, converter and alternative energy delivery systems. Each of the subsystems were mathematically modeled and joined together into a vehicle-level simulation to determine the maximum power and energy levels that result from using a worst case vehicle drive cycle. Then, these maximum levels were used as requirements for each of the subsystems so that they could be designed and sized appropriately. The simulation and modeling tools used were Matlab™ and Simulink™ from Mathworks™.

2.1 Determine Worst Case Power Demand from Propulsion System

A model of the surrogate vehicle's propulsion system (inverter and traction motor) was required to effectively size the alternative energy system (AES), DC/DC converter and energy storage system (ESS). Prior to this project, Magna Electronics developed a proprietary electric propulsion load simulator in Matlab™ that generates power versus time profiles for propulsion systems. This simulator was used to provide a realistic electrical load for the VEMS. An aggressive drive cycle, US06, was chosen for worst-case power and energy studies[1]. The minimum input parameters for the load model of the surrogate electric vehicle (1998 Ford EV) were:

- Drive cycle (US06, UDDS, etc.)
- Electric traction motor type
- Inverter type
- Transmission final drive ratio, gear box efficiency and inertia
- Maximum electric motor RPM
- Vehicle Coefficient of Drag, or dynamometer coefficients
- Vehicle mass
- Regeneration included (yes/no), and
- Tire size

2.2 Model the VEMS and Determine the Input/Output Requirements

A model was generated from the power versus time drive cycle profile and used to electrically load the vehicle energy management subsystems to determine the input/output requirements.

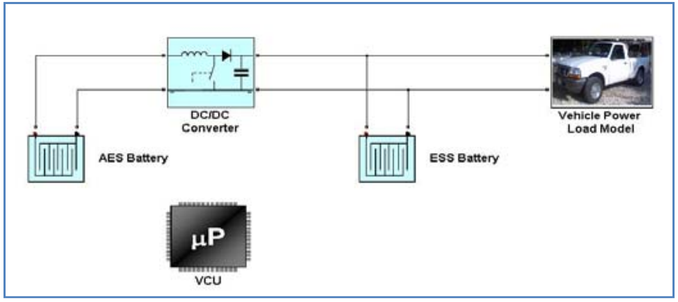

Figure 3. Vehicle Energy Management System Simulation Model

Together with an average model of the DC/DC converter and characterized Li-ion battery models of the AES and ESS, multiple simulations were run to determine the worst case power requirements of the subsystems (See Figure 3.). The VCU (Vehicle Control Unit) model reads

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[1] Kwon, J., Kim, J., Falla, E., Pagerit, S., and Rousseau, A., Impact of Drive Cycles on PHEV Component Requirements presented at SAE World Congress, Detroit, MI 2008-01-1337, April 2008.

the State of Charge (SOC) of the ESS battery and commands the DC/DC converter to provide more or less current to keep the SOC within a desired range. See Appendix A for VEMS model details.

The following results are the worst case power requirements from this simulation:

- Worse-case power output required by the inverter: 100 KW @ 400A max
- Average vehicle power load (aggressive drive cycle w/ & w/o regeneration): 17 KW / 20 KW
- High Voltage Operating Range: 240 – 350V
- Fuel cell and DC/DC converter maximum output power: 30 KW
- Fuel cell minimum voltage: 100V @ 300A max

In order to maintain a 70% SOC target for the energy storage system battery an adequate Ampere-hour capacity was required. This was 16Ah. This capacity translates into a mechanical size for the ESS that can be packaged within the battery tray of the Ford Ranger EV surrogate.

3 Implementation of the Energy Storage System (ESS)

As stated above, the project incorporates a topology that permits parallel development of the alternative energy delivery system, the energy storage system and the DC/DC converter. The worst-case subsystem requirements were defined and the Energy Storage System was implemented while the other subsystems were developed independently. The vehicle was fully-functional with the ESS installed and was road tested, however the battery capacity only allows for a limited driving range of up to five miles. The ESS replaced the existing lead acid battery system of the vehicle. The high voltage range (240-350V) and current delivery capability were maintained to avoid damaging the original components of the vehicle. The pre-existing communications from the original lead acid battery control module was kept as well as other controllers within the vehicle which rely on battery status information (SOC, range, max power allowed, voltage, etc.) from the original system.

3.1 ESS Design and Construction

Figure 4 below shows the block diagram of the ESS. The modules of the system are: Vehicle Control Unit (VCU), Battery Management Unit (BMU), Gateway module and Contactor module (interface between ESS and surrogate propulsion system) and the Li-ion battery modules. The VCU is the master of the vehicle and is responsible for controlling the charging of the batteries. It commands the turn on/off of the Ranger’s Traction Inverter Module (TIM) and Interface Adapter Assembly Module (IAA). These modules are the main controllers of the vehicle. For normal operation, the VCU, upon successful initialization will verify an acceptable battery condition from the BMU, turn on the TIM and IAA, then connect the battery to the vehicle high voltage bus through the Contactor module.

The VCU also communicates the maximum instantaneous power that can be drawn from the battery by the vehicle and the maximum regeneration power the battery can receive. In future projects, the VCU will manage how much energy is delivered from alternative energy source to the vehicle by commanding calculated levels to the DC/DC converter. A Gateway module is needed for the VCU to communicate with the vehicle controllers (TIM & IAA) because different protocols exist between the ESS and the surrogate’s Ford Standard Corporate Protocol communication bus.

There are six 52V Li-ion battery modules connected in series and each has a **V**oltage, **T**emperature, **I**-Current **M**odule (VTIM) attached. These VTIM's are responsible for instantaneous battery cell voltage, temperature and pack current measurements and communicating this data to the BMU. The BMU reads all cell voltages, temperatures and pack current, and commands which cells are to be balanced during charging. It also calculates battery pack SOC (State of Charge) and sets fault conditions when cells are out of range. The VTIM's balance the intended cell(s) during charging as instructed by the BMU. Each of the 16Ah/52V modules consist of seven cylindrical cells in parallel and 16 of these cell groups in series (7P/16S) for a total of 112 cells per module (see Figure 5*).* There are a total of 672 cells in the pack along with 42 temperature sensors and a 400A shunt for pack current measurement.

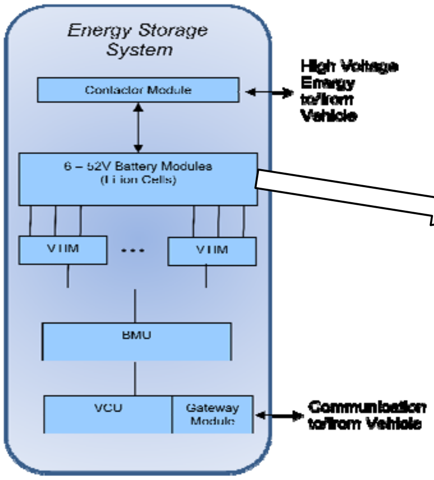

Figure 4. Energy Storage System – ESS

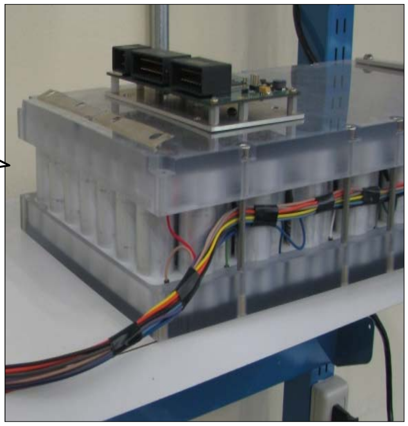

Figure 5. A Single 52V Li-ion battery module with VTIM

3.2 *Integration of ESS into Surrogate Vehicle*

All six modules are in a tray and connected in series (see Figure 6). During integration, the battery tray (approximately 3 meters long by 0.7 meters wide) which normally resides underneath the vehicle was dropped and placed beside the truck. Interface harnesses were connected from the tray to the truck allowing full access for verification testing of the electronics. Once integrated, access to the ESS is limited for diagnostics. Figure 6 also shows the battery modules and the rest of the ESS installed in the battery tray.

Figure 7 shows the entire battery tray with the ESS installed. The remaining space in the tray will be used for the DC/DC converter and alternative energy system. (Not shown are emergency stop and charge switches inside the cab of the truck.) Instrumentation to measure raw battery voltage, current and contactor status and the Emergency Power Off (EPO) signal is located in the bed of the truck. These signals are sent to the cab of the truck to a display unit on the dashboard. The EPO signal is tied to specific high voltage subsystems within the vehicle. If this circuit is opened by disconnecting a high voltage connector from a module, the main battery contactors open and isolate the battery from the vehicle high voltage bus.

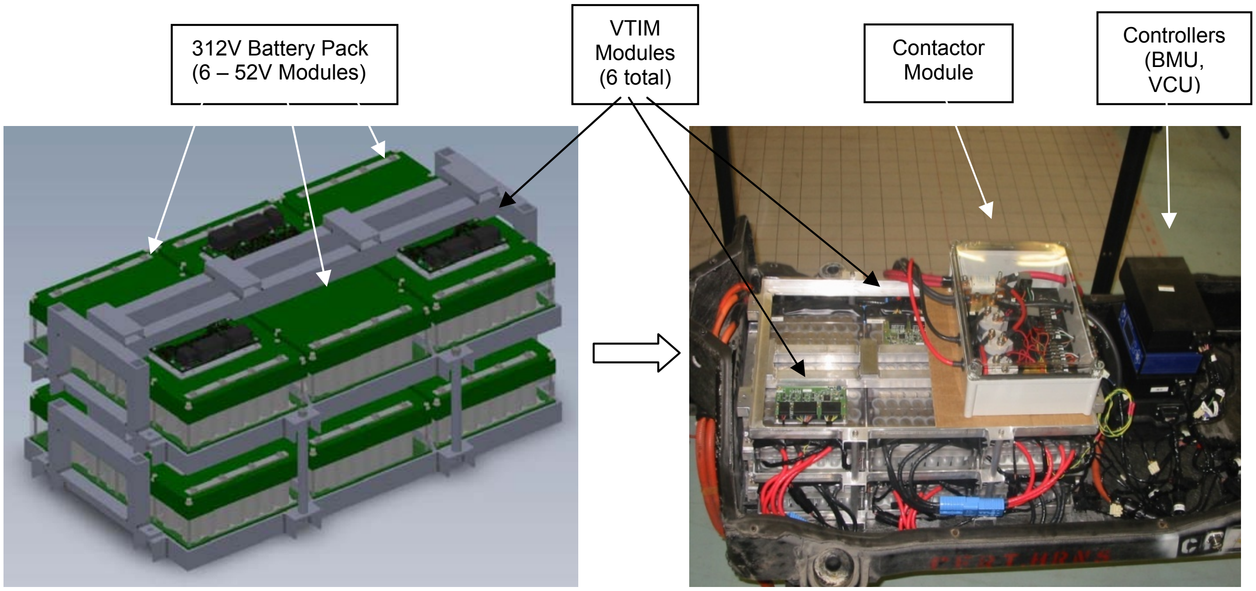

Figure 6. Six -52V Modules, Contactor, BMU and VCU Modules – Energy Storage Systems

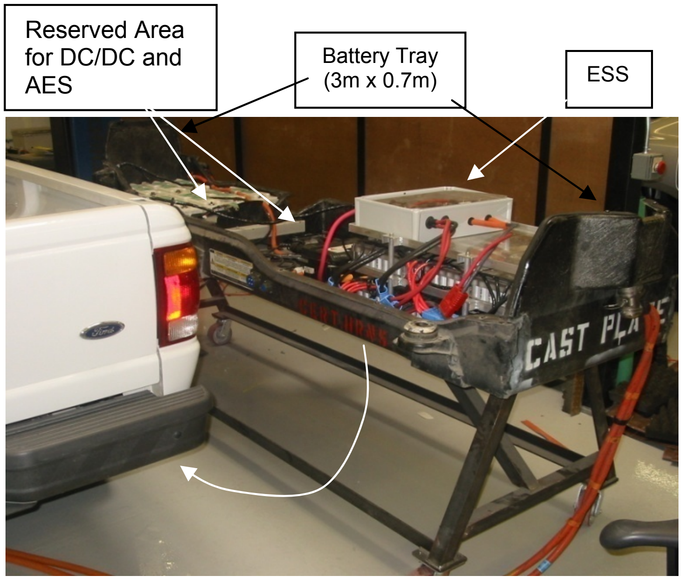

Figure 7. Six -52V Modules, Contactor, BMU and VCU Modules – Energy Storage Systems

4 Boost Converter Electronics Development

As discussed earlier, the DC/DC converter is used in this application to control power flow between the ESS and the AES. This allows the power requirements at the wheel to be decoupled from the power supplied at the source, which leads to a much lower power requirement for the AES. To determine the extent to which this system configuration allows reduction of the AES and the requirements for the DC/DC converter, vehicle level simulations were performed as detailed in section 2. Based on the initial vehicle level simulations performed, it was determined that with regenerative braking, the average power demanded by the vehicle is approximately 17 kW and the AES would be sized at a maximum power of 30 kW.

From these simulations and other vehicle level requirements, the ESS and AES systems were designed and these systems determined many of the requirements of the DC/DC converter.

4.1 DC/DC Converter Design Parameters

The relevant design requirements for the DC/DC converter from the ESS, AES, and other considerations follow:

- ESS Operating Voltage Range: 192 V to 365 V (400 V Transient)
- AES Operating Voltage Range: 80 V to 160 V
- AES Operating Current Range: 0 A to 350 A (Unidirectional Power Flow)
- AES Current Ripple: 5% of operating current, estimated impedance 0.12 Ω
- Output Voltage Ripple: 2.5% of operating voltage
- Three-Phase Interleaved Design
- Galvanic isolation not required between the input and output
- Electro Magnetic Interference, EMI, capacitors required for the input and output

As can be seen above, many of the design parameters are expanded from those shown earlier in this report. While only a unidirectional converter is required for this application, a three-phase bidirectional converter is being designed to increase the flexibility of the system. A boost converter was chosen for this project since the output voltage is always greater than the input voltage and the maximum voltage ratio is relatively small. Figure 8 shows a high level overview of the converter.

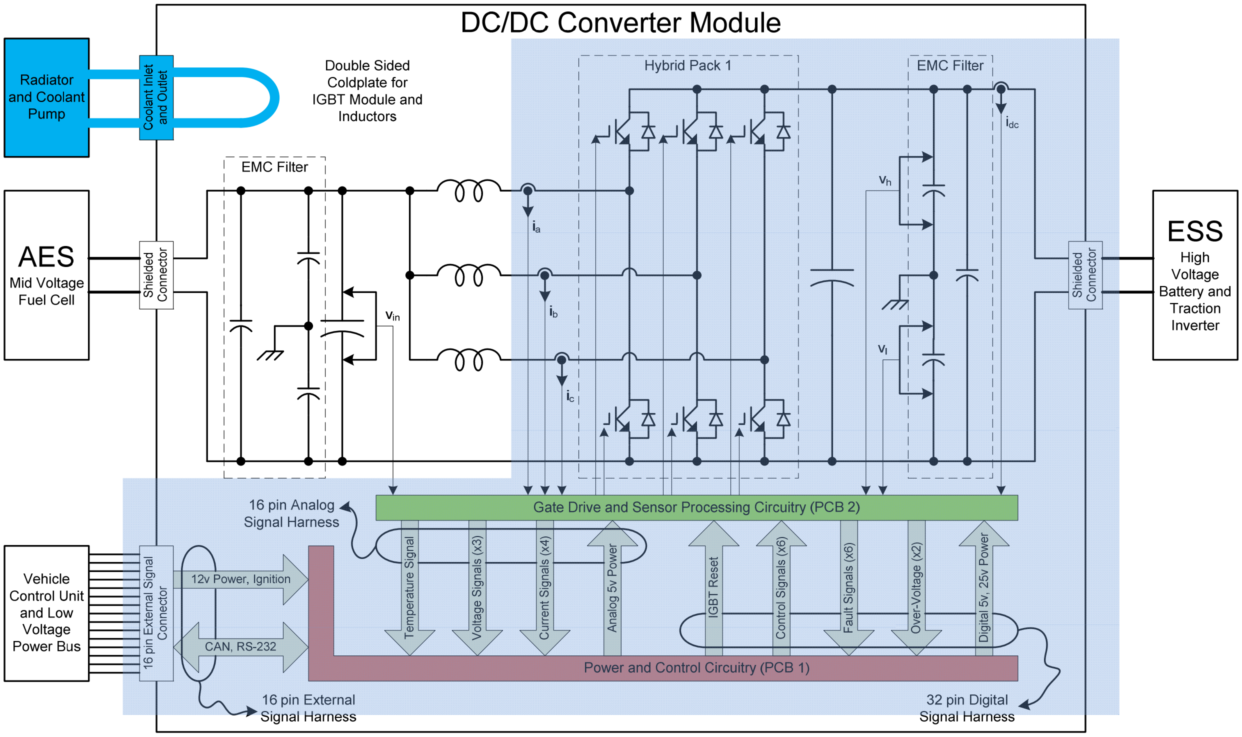

Figure 8. DC/DC Converter Overview

4.2 Design Progress

While some initial work has been done on a preliminary design of the input inductors, input capacitor, and input EMI capacitors, work to this point has focused on the power stage of the converter. The power stage includes the main switching devices, output capacitor, output EMI filter, gate drive circuitry, sensor circuitry, and power and control board. The power stage is highlighted in Figure 8 with a blue box. As a first step in the design of the converter, an IGBT module was selected, based on the requirements discussed in Section 4.1. For the initial design and testing phase, it was decided to use an existing DSP-based control board developed for another project at Magna Electronics. After these decisions were made, work focused on the design of the gate drive, sensor, and output capacitor Printed Circuit Board (PCB). The first design of this PCB was completed in November but due to an issue discovered on another PCB of a similar design, a major redesign was required to add additional area for heat dissipation. Because of this, the timing for completion of the PCB and all subsequent design and testing was pushed back by approximately 3 months. Figure 9 shows the bench-level prototype of the power stage including the DSP based control board and temporary cold plate.

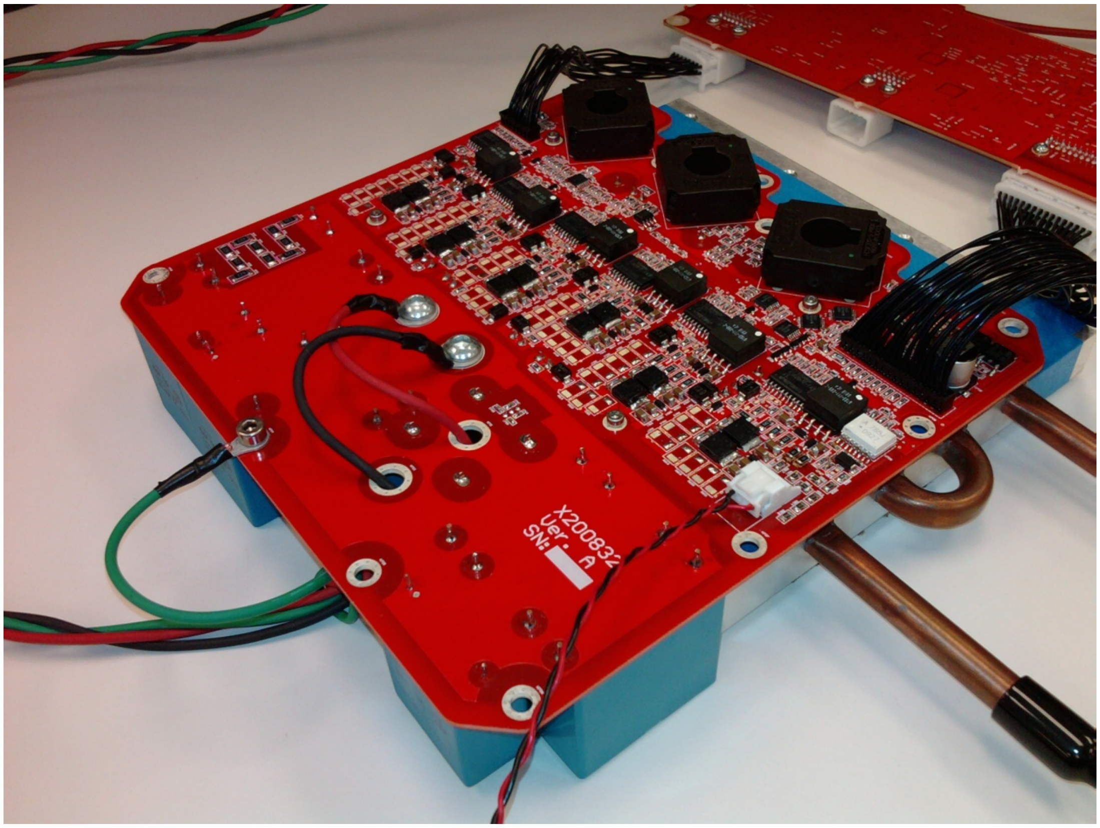

Figure 9. Bench Level Prototype Power Stage of the DC/DC Converter

The test setup shown will be used to test the functionality of the power stage. Assuming that no major issues are encountered, this setup will then be integrated with the final housing and input inductors and capacitors to finish the entire converter.

5 Conclusions

In conclusion, work was completed in three areas. First, by vehicle level simulations, sizing for the Energy Storage System and Alternative Energy Source was determined. Second, the Energy Storage System was designed, built, tested, and installed in the test vehicle. Third, using information for the vehicle level simulations, design of the DC/DC converter has proceeded with hardware complete for the main power stage of the converter.

The results of the project were:

- Design and implementation of an energy storage system into a surrogate electric vehicle
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