Low Level Design

Team HEV

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1 Introduction

The goal of our project is to hybridize an electric truck for the Metropolitan Water Reclamation District of Greater Chicago. This low level design will include a description of the problem and our proposed solution, followed by a description of our system, including a block diagram. We will then go into a discussion of specific technologies we will be applying in the course of our solution and the list of system requirements our team will need to fulfill in order to design, build, and test our hybridized electric truck.

2 Problem Statement and Proposed Solution

The Metropolitan Water Reclamation District of Greater Chicago currently owns a fleet of purely electric trucks. These trucks are used for projects requiring driving ranges less than 30 to 40 miles per charge. However, they would like these trucks to have the capabilities to perform jobs that require driving distances further than 40 miles. In order to provide this capability, they have asked us to transform this purely electric vehicle into a hybrid electric vehicle. The goal is to reach a city mpg rating between 60 – 80 mpg (50 mpg minimum). They would also like to see an increase in speed capabilities—from 25 mph to at least 35 mph. Our goal is to reach a maximum speed of 40 mph. An additional complication to this situation is that they require the option to undo any changes we make during the hybridization process if they choose to revert back to the purely electric version.

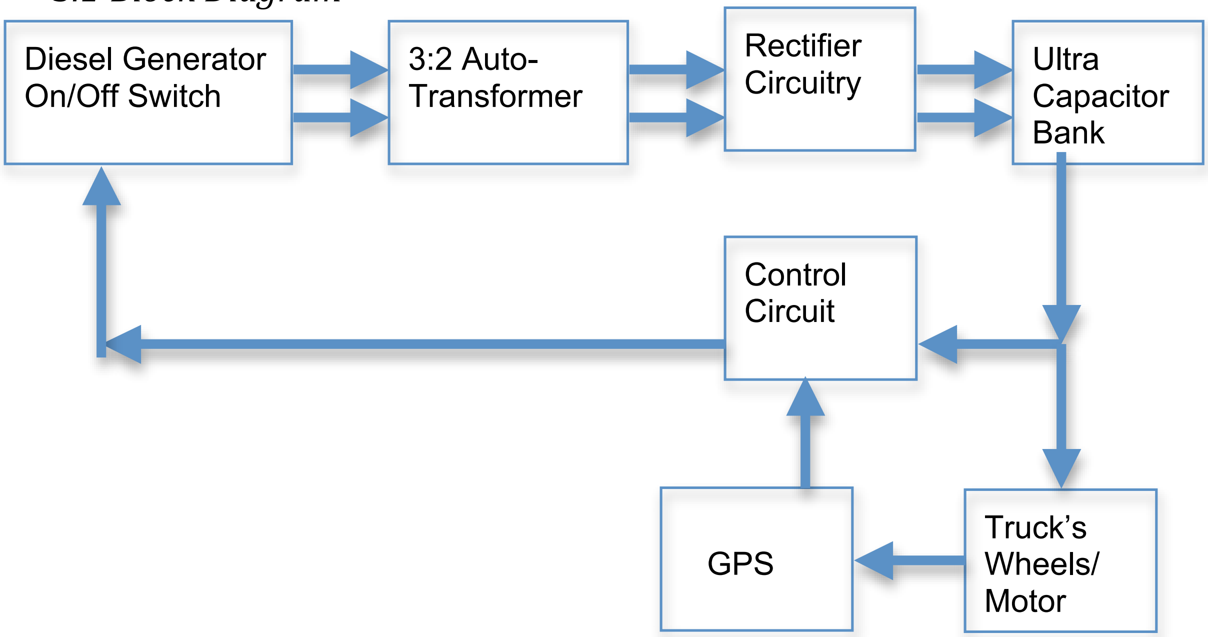
Instead of lead batteries, we will use ultra-capacitors as our primary energy storage unit. The ultra-capacitor bank has a few key advantages over lead batteries. First, the ultra-capacitor bank is lighter than the lead battery collection, which will help decrease the weight on the truck and improve fuel efficiency. Additionally, ultra-capacitor banks can be charged/discharged many more times than lead batteries; according to Professor Bauer, the ultra-capacitor bank could go through the lifetime of about three trucks before their charging ability begins to degrade.

By using an ultra-capacitor bank instead of batteries, we needed to develop a method of effectively charging the ultra-capacitor bank. Instead of using a traditional internal combustion (IC) engine, we plan to use a diesel engine. The diesel is more efficient and will directly power the ultra-capacitor bank. In order to charge the ultra-capacitor bank, we will need to control when the diesel is turned on and off. To do this, we will design a controller to monitor the voltage levels of the ultra-capacitor bank. The microcontroller will send a command to turn the diesel engine on once the voltage of the ultra-capacitor bank falls below a certain threshold, and will send a command to turn the diesel engine off once the voltage of the ultra-capacitor bank has exceeded an upper threshold.

We intend to build functionality into our microcontroller that will go beyond the basic function of turning the generator on and off. We will be implementing a system to monitor the driving schedules of the driver in order to ensure proper charging of the capacitors. The primary concerns we have regarding the charging involve climbing hills and regenerative breaking. We will implement a GPS device to monitor the altitude changes of the truck. This information will allow us to estimate the energy being drawn from the ultra-capacitor bank; from this we will determine whether the generator should turn on to increase the charge in the bank to ensure the truck has enough energy to climb a hill. Regarding regenerative breaking, we will be monitoring the current coming into the ultra-capacitor bank; using this information we will be able to ensure that we do not turn on the generator when the bank is close to full charge due to the regenerative breaking current.

3 System Description and Block Diagram

3.1 Block Diagram



3.2 System Description

Diesel Generator: On/off Switch

The On/Off switch on the 6 kW diesel generator is a mechanical system. However, we have found a way to bypass the mechanical switch to control the generator electrically. We will describe in the low level design section how we have implemented the controls for this function.

3:2 Auto-Transformer

The original 2:1 transformer is wired as an autotransformer with a ratio of 3:2. It takes in an AC voltage from the generator and output an AC voltage that is reduced by 33%.

Rectifier Circuitry

The full-bridge rectifier circuitry converts the AC voltage input into a DC voltage output. This is required in order to charge our ultra-capacitor bank.

Ultra-capacitor Bank

The ultra-capacitor bank is charged by the rectified DC current coming from the transformer through the rectifier circuitry. Each individual capacitor has a corresponding balancing circuit to regulate its charge, keeping the charge of the capacitors relatively equal.

Control Circuitry

The control circuitry takes the following inputs:

- Three (3) current sensors
- Ultra-capacitor voltage divider
- Temperature sensor

Its output includes:

- On/off generator signal
- Starter Signal
- Glow plug signal

It takes the signals from the inputs to signal the microcontroller what actions need to take place via the output signals.

Trucks's Wheels/Motor

The overall system feeds power into driving the wheels/motor of the truck. In order to successfully power the wheels, we need our overall system to provide between 55 V to 80 V. Since the ultra-capacitor bank directly powers the motors/wheels, we want our ultra-capacitor bank to stay within an operating voltage of 55 V to 80 V.

The microcontroller acts as the "brain" of the whole system; it knows when to switch on and off the diesel generator. We will to power our microcontroller with the battery on the diesel generator. The battery outputs 12 VDC, but our microcontroller can only take up to 3.3-5 VDC. We will use a voltage regulator to bring the battery output down to a level suitable for our microcontroller.

The user interface required in this project include operating the vehicle (driving/gas pedal/break mechanisms), manually turning on and off the generator (fail-safe mechanism), monitoring the fuel consumption, and globe plug warming mechanism. The manual control of the generator is intended to serve as a fail-safe mechanism for preventing the over or undercharging of the ultra-capacitor bank. If the part of the control circuitry in charge of telling the generator to turn on and off in reaction to the ultra-capacitor bank charge is not working, we must create a user interface to allow the continued operation of the truck. This will require a notification of the ultra-capacitor voltage levels. If the levels become too high, the user will be instructed to turn the generator *off* manually. Similarly, if the voltage level becomes too low, the user will be instructed to turn the generator *on* manually. The fuel monitoring will be more of an estimating process. We will use the data from the GPS to determine the distance the truck has traveled. After estimating efficiency of the truck, we will be able to estimate when the fuel level of the generator is low. Our system will notify the user of this, and once the generator tank has been refilled we will require the user to reset the fuel monitoring system. The globe plug interface prevents the user from attempting to turn on the vehicle when the generator is too cold. The user will be notified when the globe plugs need to be warmed before starting, and then when it is okay to start the truck.

We plan to install the system under the truck; thus, we need to be careful how we mount everything. There are several factors that we considered. First, we need to use heavy duty bolts in order to hold everything below the truck; the diesel generator is too big to be mounted on the bottom, so instead it will be put on the bed of the truck. Additionally, we need to consider how to insulate all the components. Rain and snow can ruin the electronic components if the components are not insulated properly. The only part of our project that requires modifying the original electric truck is the interfacing between the ultra-capacitors and the wheels. Since our project deals with immensely high voltage and current values, safety is definitely an issue that we must consider. The voltages and currents we are working with are high enough to kill somebody; thus, we will be carefully insulating each of our electrical components. This will protect the components from the weather and the users from electrical danger.

GPS

The GPS will serve two purposes for our project. First, because we intend for our system to serve as a research prototype for further design, our GPS will collect data regarding our latitude and longitude movements. The GPS module will interface to the microcontroller through a SD card. With this data we will be able to determine velocities, and by graphing the driving schedules we will better understand the fuel efficiency of our design.

Secondly, the GPS will serve as a control mechanism for charging the ultra-capacitors. The altitude reader on the GPS will be used to monitor when the vehicle is climbing a hill. Because climbing a hill might create a situation in which the vehicle draws an unexpected amount of energy (over a fairly small time period) from the ultra-capacitor stack, monitoring the altitude will allow us to determine if we need to turn the generator on due to a low stack voltage.

4 System Requirements

4.1 Overall System

Our system will enable a driver to operate a hybrid electric truck. We will demonstrate in May that we can successfully do the following:

- Drive the hybrid electric truck, showing that the generator turns on automatically when the ultra-capacitor bank levels fall below 55 V and turns off automatically when the bank voltage reaches 80 V.
- Monitor the temperature of the generator in order to ensure that the globe plugs are warm before the vehicle is started. If the temperature is too low, we will be able to notify the user that our system must be allowed to warm the globe plugs before starting the vehicle.
- Achieve the desired fuel efficiency of at least 50 mpg. This will demonstrated through testing in late April. The data we gather through this testing will allow us to determine the fuel efficiency of the hybrid electric truck.
- Achieve the increased speed capabilities of 35 mph.

4.2 Subsystem Requirements

Diesel Generator: On/off Switch

The following are the primary requirements of the diesel generator on/off switch:

- Send a 12V signal to turn on the generator, bypassing the internal 12V signal that is controlled by the generator
- Send a 0V signal to turn off the generator

3:2 Auto-Transformer

The following are the primary requirements of the auto-transformer:

- Prevent shorting through safe and robust connections.
- Ensure the dot conventions of the coil windings are in line to prevent magnetic flux from cancelling out, thus potentially destroying the transformer.
- Support a higher level of current than the original 2:1 transformer.

Rectifier Circuitry

The following are the primary requirements of the rectifier circuits:

- Produce a DC signal output from the AC signal input via a full-bridge rectifier.
- Handle at least 100 A of current together. (Since we use 10-gauge wires that handle a maximum of 35 A, we will use 3 in parallel.)
- Make robust and safe connections to prevent shorting.

Ultra-capacitor Bank

The following are the primary requirements of the ultra-capacitor bank:

- Charge at least to 50 V with 80 A of current in order to create 4 kW of power.
- Limit the voltage on each ultra-capacitor to less than 3 V.
- Balance the voltages on each ultra-capacitor to prevent an ultra-capacitor from charging too high, causing an possible explosion of the ultra-capacitor.

Control Circuit

The following are the primary requirements of the control circuit:

- Measure current from the battery to the solenoid connected to the starter
- Limit the time duration of the 12V signal to the solenoid, to protect the starter
- Measure the voltage across the ultra-capacitors
- Activate the on/off circuitry based on the ultra-capacitor voltage level
- Measure temperature around the glow plugs, and send a 12 V signal to warm up the glow plugs if the temperature is too cold

GPS

The following are the primary requirements of the GPS subsystem:

- Implement the wireless antenna in order to transmit the signal between the GPS satellites and the module.
- Successfully interface to the microcontroller to read latitude, longitude, and altitude data onto the SD card.
- Create a package design to protect the module from environmental hazards. These hazards include physical contact with other items in or on the truck (due to driving—i.e. bumps) and inclement weather.

4.3 Future Enhancement Requirements

We project that future consumers of our project may face the same dilemma the Metropolitan Water Reclamation District of Greater Chicago faces. They purchased a fleet of electric trucks with the "green" movement in mind; however, because of the current state of technology, these purely electric trucks could not satisfy all of their requirements. We propose for future enhancement a switching mechanism that would allow the user to choose when he or she would require hybrid technology. For example, if the user was only operating within the ultra-capacitor's driving range, he or she might choose to forego use of the generator. We would also propose adding some sort of external charging system for the ultra-capacitor bank to facilitate this mechanism further. The user could then choose to plug in the vehicle, much like an electric car today, to restore charge in the ultra-capacitor bank.

We are currently operating the ultra-capacitor stack at a maximum voltage of 2.5 V, which is under the maximum allowable voltage of 3.2 V. A possible future enhancement to this project is to continuously operate each capacitor at the maximum value.

5 Low Level Design

5.1 Diesel Generator: On/off Switch

We used MOSFET circuitry to control the electric signal to the fuel valve. When the microcontroller sent a 3 V signal to the P-type MOSFET, the output from the N-type

MOSFET was high, which is the 12 V passed from the battery of the generator. When the microcontroller sent a 0V signal to the P-type MOSFET, the output from the N-type MOSFET was low, which is 0V. We sent either the 0 or 12V signal to control the opening or closing of the fuel valve. A 12 V signal opened the fuel valve, allowing diesel to flow and run the generator, while a 0 V signal cut off the flow of diesel.

5.2 *3:2 Auto-Transformer*

Initially, we used a generic 2:1 transformer and connected it in the high current configuration. However, after running a charging test with it, we found that the current that is ultimately delivered to the ultra-capacitor stack is too small (25 A at 50 V, which only corresponds to just over 1 kW of power). We hypothesized that the small current is due to the fact that the voltage difference between the fully rectified DC signal and the ultra-capacitor stack voltage is not high enough; thus, to solve this problem, we decided to try a transformer with a smaller ratio than 2:1.

We applied the idea of an autotransformer because an autotransformer can be wired so that a variety of voltage ratios are possible. We chose to wire it as a 3:2 autotransformer as a test, to see if we could get enough current through the ultra-capacitors. Since the transformer has 4 coils, we were able to take 2 coils each for 2 autotransformers. This allows our high current levels to flow in parallel. Through the test that we ran with this configuration, we found that the ultra-capacitor stack can be charged with 80 A of current at 50 V, which corresponds to 4 kW. This power level is sufficient to drive the wheel motors.

5.3 *Rectifier Circuitry*

The rectifier circuitry consists of three 600 V/50 A full bridge rectifiers connected in parallel. They take an AC input voltage from the low end of the transformer and output a fully rectified DC signal. Initially, we picked 25 A rectifiers; however, after realizing that a total of 75 A would not be enough for our application, we changed the design to incorporate 50 A rectifiers. This allows us to have a total current of 150 A, which is more than enough for our application.

When making the connections to 10 gauge wires, we decided to use screw-on connectors instead of crimp-on connectors. We did not choose crimp-on connectors because it is a permanent connection, which makes future modifications to the system almost impossible. We chose screw-on connectors because they are robust and well-insulated.

5.4 Ultra-capacitor Bank

Our ultra-capacitor bank consists of 32 ultra-capacitors connected together in series. Since each ultra-capacitor has a maximum voltage rating of 3 V, the entire stack will have a maximum of 96 V, which is well above our maximum operating voltage of 80 V. With 80 V across the entire stack, we will have about 2.5 V across each ultra-capacitor. Our minimum operating voltage for the ultra-capacitor stack is 50 V, which corresponds to about 1.6 V per ultra-capacitor.

In order to solve the balancing issue with the ultra-capacitor bank, we initially tried to use power diodes. Due to the non-linear nature of diodes, we want the diodes to dissipate large amounts of current when the voltage of the ultra-capacitors get above a certain level (like 2.7), and hardly dissipate any current at lower voltages (like 2.5 V). However, we found out that high-powered devices are not as non-linear as we hoped; thus, using these devices became unfeasible.

We eventually decided to test low-powered diodes, and we found the non-linear characteristics of generic 1N4001 diodes to be highly appealing. Our final configuration consists of three of these diodes connected in series. This configuration is then connected to each ultra-capacitor. Through experimentation, we found that the current at 2.5 V is just under 50 mA, but, once the voltage on the capacitor increases to 2.7 V, the voltage jumps to 0.7 A. This is the non-linear characteristic we need to complete our balancing circuitry successfully. The purpose of the balancing circuitry is to dissipate high current at higher voltages and low current at lower voltages, making capacitors with higher voltages decrease faster than capacitors with lower voltages. This eventually balances the entire stack out, minimizing the potential for overcharging.

<u>Charging Circuitry:</u>

I. Schematic Diagrams

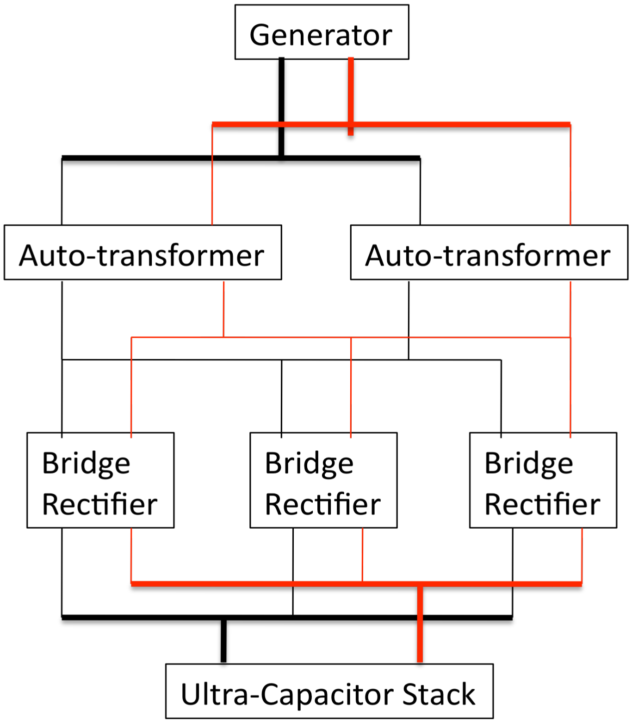


Figure: The black wires are neutral lines, and the red wires are hot lines. The thick wires are 3 gauge, while the thin wires are 10 gauge.

II. Circuit Description

We removed the front panel from the generator in order to bypass the outlets on it. This allows us to tap directly into the hot wire from the generator, resulting in better connections than those possible using the outlets. The hot and neutral wires supply a 120 VAC signal, which we are sending to the transformer. We wired the 2:1 transformer into two 3:2 autotransformers, and thus we split the hot and neutral into parallel lines and fed them into the two autotransformers. The two sets of wires coming out of the transformer will then split into three sets of 10 gauge wires, all feeding into the full-bridge rectifiers. The three sets of wires then merge into 4 gauge wires that feed into the ultra-capacitor stack.

For our ultra-capacitor stacks, we built a diode circuit in order to balance the voltages on each capacitor. Each diode circuit consists of three 1N4001 diodes connected in series; the balancing circuit allows capacitors with higher voltages to dissipate higher currents, and the capacitors with lower voltages will dissipate less current. Eventually the voltage on each ultra-capacitor will reach similar levels.

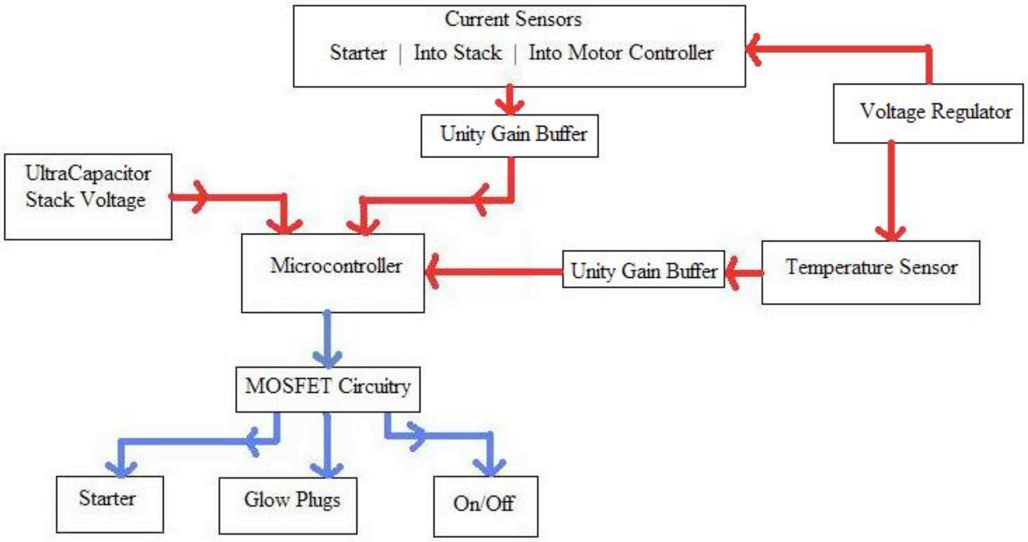
Making robust connections is essential in our project. Thus, each of components in the balancing circuits has been soldered and insulated.

III. Testing Plan

Our initial testing involved alternating the connection from the generator to the transformer; instead of tapping directly into the hot, we used two AC plugs that connects onto the front panel on the generator. Due to the bulkiness of the transformer, testing the charging circuitry with the generator every time is not feasible, since we have to push everything outside. So instead, we tested the charging circuitry by putting the AC plugs into wall outlets. Our first tests were done with a 2:1 transformer under the regular configurations, but the current we were getting out of the generator was not high enough—we could only get a power of 2 kW into the ultra-capacitor stack. This is due to the fact that the voltage difference between the voltage on the rectifiers and the voltage on the ultra-capacitor stack is not big enough. This caused us to make the autotransformer modification, which allows for a greater voltage difference, and subsequently a much higher current (corresponding to 4 kW of power, which is sufficient for our application).

5.5 Control Circuit

I. Schematic Diagrams



II. Programming Flowchart

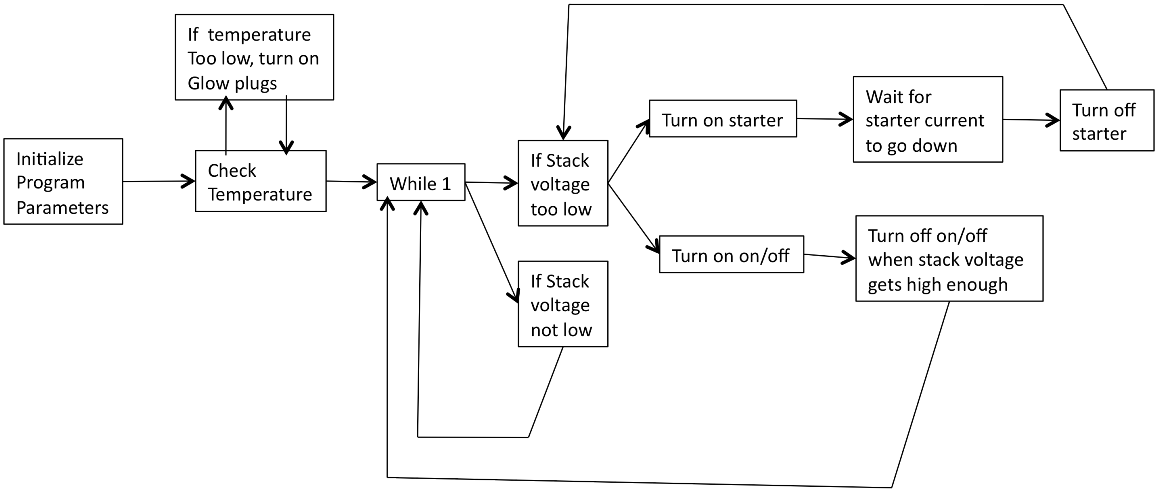


Figure: This is the central part of the program. The turning on and off the generator is dependent on the ultra-capacitor stack voltage.

III. Circuit Description

All of our circuitry is centered on our microcontroller. We have five different input pins corresponding to three current sensors, a temperature sensor, and the ultra-capacitor voltage. The four sensors require a 5 V power supply. However, our only voltage source is the 12 V battery on the generator. To step down the voltage from 12 to 5 V, we used a 5 V voltage regulator. To protect the voltage regulator, we added a capacitor to both the input and output. Next, we passed the signal through a unity gain buffer, which protects the sensors from the microcontroller sending a signal to the sensors. Additionally, the unity gain buffer helps by providing impedance protection, reducing the chance of a short circuit. The signal entered the microcontroller after passing through the unity gain buffer.

The microcontroller used A/D conversion on the inputted voltage signals and output a 0 or 3.3 V signal. The 3.3 V signal to the starter was time limited, and only stayed high at 3.3 V until the starter current sensor detected a current of over 25 A passing through. This value was fed back to the microcontroller, which in turn set the signal low to 0 V.

For the glow plug signal, the value from the temperature sensor was fed back to the microcontroller. If the temperature sensor's voltage was over a programming threshold, then it set the glow plug signal low, from 3.3 V to 0 V to turn the glow plugs off.

The 12 V signals were sent to the on/off circuit, the starter circuit, and the glow plugs. We used this same MOSFET circuitry to produce each of the three 12 V signals.

IV. Testing Plan

The MOSFET circuitry was first laid out on a breadboard. We input a 3.3 V signal to the circuit to simulate receiving a signal from the microcontroller and we used a 12 V signal from the power supply to simulate the voltage from the battery on the generator. We used a voltmeter to measure the output signal and verified that we had a 0 V output for a 0 V input and a 12 V output for a 3.3 V input. As we varied the input voltage from 0 V to 3.3 V, the circuitry correctly changed the output from 0 V to 12 V when we passed a threshold of V_{in} = 1.2-1.5 V.

After the tests were verified on the breadboard, we soldered our components onto a perf board and repeated our tests. Once this was complete, we were able to test our circuit using a signal from the microcontroller and the battery on the generator. We simulated the voltage across the ultra-capacitor stack by using a variable resistor with an A/D converter for the microcontroller. With this microcontroller input and the 12 V battery source, we verified our prior results.

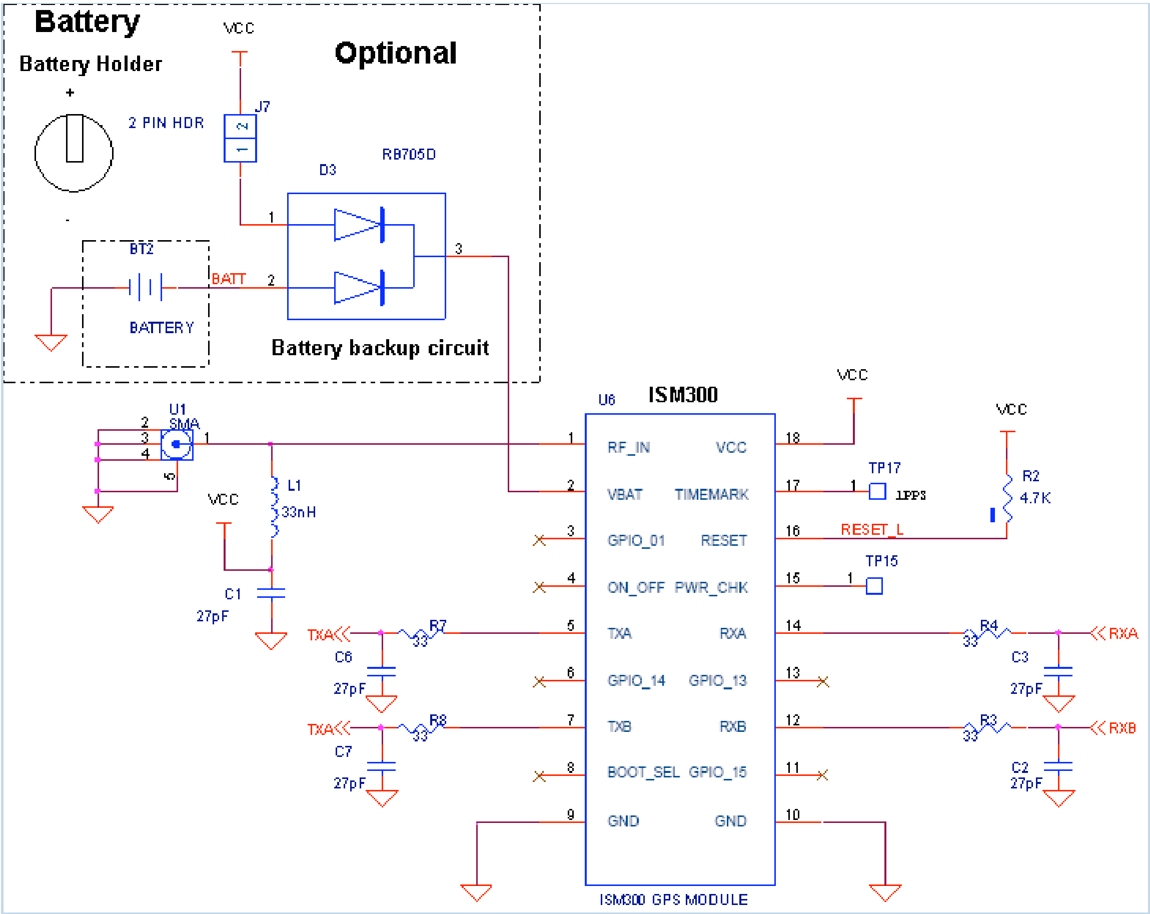
Following this test, we connected our current sensors and temperature sensors to a breadboard. We put a varying current of 0-2 A through the current sensor. As the current increased, the voltage reading at the output of the current sensor increased by 12 mV/ 1A. We verified the functionality of the temperature sensor by placing a heat source next to the sensor and measuring the output voltage. Using a soldering iron to heat up the sensor, we observed an increase of 11 mV/°C.

The last test we will do is measuring the voltage across the ultra-capacitors and verifying that the microcontroller's A/D converter can process the voltage and send a 0 V signal to turn off the microcontroller upon passing the upper voltage threshold of 80 V.

5.6 GPS

We have chosen to implement the Inventek Systems ISM300F2-C4 GPS module. We chose this device because of its ability to monitor latitude, longitude, and altitude using a serial port interface. The voltage required to power the device is 3.3 V, a level compatible with our system. Additionally, we found moderate cost savings in choosing this device over a Garmin device, and the documentation made available on the Inventek Systems website will ease our design process greatly. When we receive the GPS module, we will begin determining how to implement the antenna (RF) interface. While we prefer to use one of the GPS antennas Dr. Schafer currently has in his office, Inventek Systems does sell compatible antennas for this module.

I. Schematic Diagram



II. Standard Interface

This device has two standard serial communication interfaces available. Each are implemented by a universal asynchronous receiver/transmitter. The two default protocols for reading data SiRF binary and NMEA-0183. We will determine which protocol is best for our use once we receive the GPS module.

III. Testing Plan

Testing of the GPS system is not much unlike implementing it on the actual truck. The ideal testing environment would be to operate the vehicle according to a planned driving schedule, making sure to include a hill. Once we returned to the lab, we would ensure that the correct data could be read from the SD card on the microcontroller. We will be working on this interface—hopefully with the help of Rob Jones—once we receive our GPS module. If our truck is not ready to operate when we are ready to test the GPS system, we will likely use conduct the driving schedule using one of our own cars. This would require bringing the microcontroller and the GPS module and antenna into/onto this car, so it would have to happen before we made any of the semi-permanent attachments of the board to the truck.

6 Bill of Materials

Diesel Generator - 7 kW
Transformer - 5 kVA
3 Bridge Rectifiers - 50 A 600 V
32 Capacitors - 3000 F
96 1N4001 Diodes
GPS Module - 3.3 V input requirement, Serial Interface
Microcontoller
3 Current Sensors – 150A
1 Temperature Sensor: -55° to +150°C
3 N-Channel MOSFETs - 60V, 32A
3 P-Channel MOSFETs - 50V, 9.9A
6 Resistors - 1kΩ
4 Dual Operation Amplifiers
1 Voltage Regulator – 5V output
1 Capacitor 0.33 μF
1 Capacitor 0.1 μF

7 Conclusions

We have examined the input/output characteristics of each component in our design. These features have allowed us to construct the overall system that we need to create in order to accomplish our goal. In the coming weeks, we will be working on designing the board and the GPS-SD card interface.

8 References

8.1 GPS Module Functional Specifications

http://inventeksys.com/specs/ISM300F2_Functional_Spec.pdf