DC House
Energy Management System

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Abstract

In this work, a previously completed proof of concept for an Energy Management System (EMS) for the DC House project has been revised and re-implemented. The implemented design changes will improve the performance and reproducibility of the system. This new design of the EMS replaces the two-separate buck and boost DC-DC converters with a single bidirectional DC-DC converter to reduce components and improve efficiency. Analysis of the bidirectional DC-DC converter shows high efficiency especially at larger load currents. The code of the previous work was updated for smoother operation as well as to accommodate an LCD capable of displaying more information. This project also makes use of the temperature sensing capabilities of the state of charge sensor selected in the previous design to allow for a better understanding of the system's operation. Additionally, the sensor and all passive components were incorporated into a printed circuit board to create a more reproducible product. Testing of the system demonstrated its ability to successfully direct power between the 48V DC bus and load and the 12V battery.

Chapter 1. Introduction

Electric power is essential to modern life. As the ability to store and transmit power improves, so do standards of living. One such improvement was the development of power electronics. Power electronics is an area of electrical engineering that focuses on efficiently controlling the flow of electric energy by using solid-state switches and other electronics. Power electronics is everywhere. Over 40% of the world’s electric power generated utilizes power electronics systems. The emergence of switched-mode power supplies to replace large linear power supplies allowed advancement in a wide range of industries that now rely on power electronics. Some examples of these systems are: consumer electronics (smart phones, laptops), power supplies, renewable energy, data centers, transportation (electric vehicles, trains), and DC-DC converters. During the power conversion process, power electronics aims to achieve two goals. The first goal focuses on having a small power loss. This, in turn, leads to high energy efficiency which means lower cost. The second goal of power electronics is to decrease the size and weight of the system, also leading to a lower cost [1].

The design of power converters relies heavily on power electronics. The different types of power converters are rectifiers (AC-DC), inverters (DC-AC), AC-AC converters, and DC-DC converters. Rectifier and inverter circuits take one form of electric energy (AC or DC) and convert it to the other (DC or AC). AC-AC converters take AC power and convert it to a different level and/or frequency of AC power through circuit designs such as phase control and integral cycle control. DC-DC converters take DC power and convert it to different levels of DC power [1].

The use of DC power by many devices and household electronics makes DC-DC converters especially prolific. DC-DC converters come in two main types, isolated and non-isolated. Isolated DC-DC converters utilize transformers while non-isolated DC-DC converters do not. The non-isolated topologies include for examples the buck converter, the boost converter, and the buck-boost converter. The step-down buck converter is essential due to the need for high line voltages to be stepped down to lower voltage levels required by different devices. The step-up boost converter produces a higher voltage output from a lower voltage input [2]. This function is needed for transferring power back to a grid; for example, renewable energy sources like solar and hydro powered generators.

The desire to utilize clean sources of energy has led to expansion of renewable energy production. The distribution of power from a large central plant is disadvantageous due to losses during transmission. This drives the need for smaller scale power sources such as rooftop photovoltaics [4]. Renewable energy sources are naturally not stable resources of constant energy. The use of a battery and battery management makes renewable energy sources more reliable and practical for widespread use [3]. The function of transferring power from a battery to a higher voltage bus or from a higher voltage bus to be stored in a battery requires the functionality of a step-down and a step-up regulator. The converter system between a DC bus and a battery must therefore allow for a bidirectional power flow.

Chapter 2. Background

Renewable DC Energy and the DC House Project

The DC House Project is a humanitarian effort that aims to bring electricity to rural areas. Locations that are too remote to afford or have access to conventional AC power distribution are prime candidates to utilize renewable energy sources such as hydro, wind, and solar power. Designing a house to use DC power from DC renewable sources also bypasses AC to DC conversion and losses associated with conventional AC houses [3]. The operation of the DC House is based on DC renewable power generators connected to a DC bus by a Multiple Input Single Output (MISO) controller. The DC bus also connects to a battery system and to the DC House. Energy storage compensates for the inconsistent nature of renewable sources such and wind or solar. An energy management system (EMS) is required to control power flow and direction on the DC bus [5]. Figure 2-1 shows the basic block diagram of the whole DC House system.

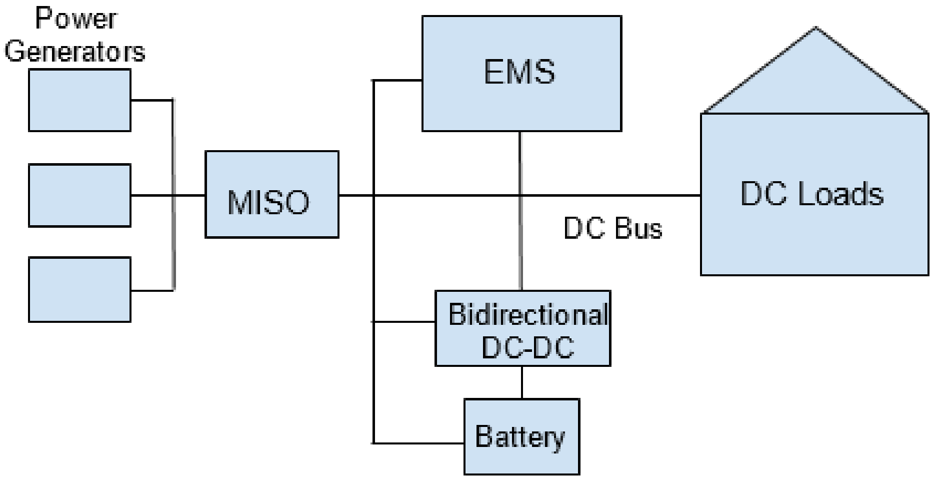


Figure 2-1: DC House Block Diagram Overview

Energy Management for the DC House Project and Current Implementation

The current Energy Management System (EMS) for the DC House (as reported in [5]) controls energy flow on the 48V bus between the MISO, 12V battery system, and devices inside the DC House. This EMS charges or discharges the battery depending on available power and demand from the load. The system also protects the battery by regulating its operation. The chip used for battery monitoring is the BQ78412 which is designed to work with single 12V Pb-Acid batteries. This state of charge (SoC) indicator is capable of monitoring battery voltage, current, and temperature and calculating runtime-to-empty [7]. The system uses an Arduino microcontroller, display, and relays that engage the converters between the battery and the DC bus [5].

Several design changes could improve the operation of the EMS. In the current implementation, the EMS does not include temperature monitoring of the battery. Sensing temperature would make a safer and more robust system. Additionally, the current design lacks a PCB layout. Implementing the entire EMS system in a PCB layout would reduce production costs and create a more easily reproducible product [5]. Lastly, the current EMS system utilizes two DC-DC converters; one Buck (step-down) converter used to step down the DC bus voltage to charge the battery, and one Boost (step-up) converter used to step up the battery voltage to supply power to the DC House. The use of two separate converters is costly, inefficient, and requires excess physical space. A design using a single, bidirectional converter would be an improvement in price, efficiency, and size.

Improving the Current EMS System

The purpose of this project is to build and improve upon the existing Energy Management System (EMS) to create a more efficient and cost-effective solution. The new EMS system will still perform the same duties as that of the present system. It will control the flow of energy between the DC bus, batteries, and the DC house. The EMS will also still protect the batteries from overcharge and deep discharge. The improvements and additions that are going to be the main focus of this project are as follows:

- Replace two-converter Buck and Boost system with a single Bidirectional converter
- Add battery temperature and state of charge (SoC) sensing
- Create a PCB design to increase product reproducibility

These improvements should all improve the overall efficiency of the EMS systems as well as lead to a low-cost and easily reproducible product.

Chapter 3. Design Requirements

The Energy Management System (EMS) is designed for the users of the DC House. For this purpose, the entire EMS system is required to be efficient, safe, and affordable. It must be reliable and be protected by a weather resistant enclosure. The first step to design the EMS system for the DC House was to determine the basic inputs and outputs of the system. The inputs are the 12V Battery bank and the 48V from the DC Bus and the MISO. The outputs of the EMS system are the 12V Battery bank and the 48V to the DC Bus and the house load. Figure 3-1 shows the “Level 0” block diagram with these inputs and outputs.

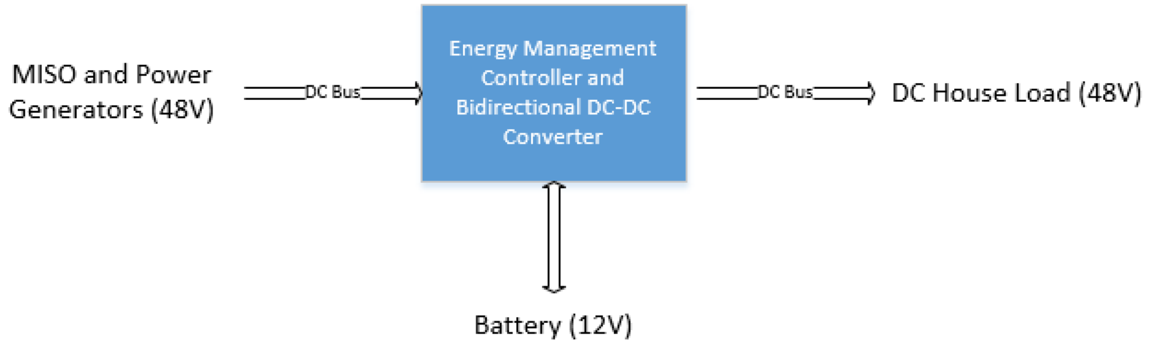


Figure 3-1: Level 0 DC House EMS Block Diagram

The Level 0 block diagram in Figure 3-1 shows the basic functionality of the EMS system. The DC House Loads will demand a certain amount of power based on the present usage in the house. If the power generators can supply this level of power to the MISO and DC Bus, the EMS system will accept input power from the DC Bus (and MISO) and direct it to the DC House load. When the power generators cannot supply enough power, additional power from the battery bank will be input into the EMS system and converted to supply power to the DC House (batteries take on the role as inputs here). When the power generators supply excess power, the extra power will be supplied from the DC Bus to charge the batteries until fully charged (batteries change role to outputs here).

From these basic high-level design choices, more in-depth design choices can be derived. For starters, one of the primary goals of this project was to improve upon the conversion system between the 12V battery bank and the 48V DC bus. Previously, two separate DC converters were used (one step-up and one step-down). The design of this project implements a single, bidirectional DC-DC converter [8][9]. The use of a bidirectional converter will allow of a higher efficiency, lower cost, and a more technologically advanced system.

To determine the state of charge (SOC) of the battery, a SOC chip was needed to monitor battery voltage, current, and temperature levels. The SOC chip will allow for critical measurements to avoid overcharging or deeply discharging the batteries. This complex chip, along with other signals to monitor DC bus current and voltage, need to be controlled and monitored by a microcontroller. Furthermore, the bidirectional controller requires some input signals to switch between its step-up (Boost) from 12V to 48V and step-down (Buck) modes from 48V to 12V. These signals will also be controlled and output by the microcontroller. These design additions can be viewed in the Level 1 block diagram of Figure 3-2.

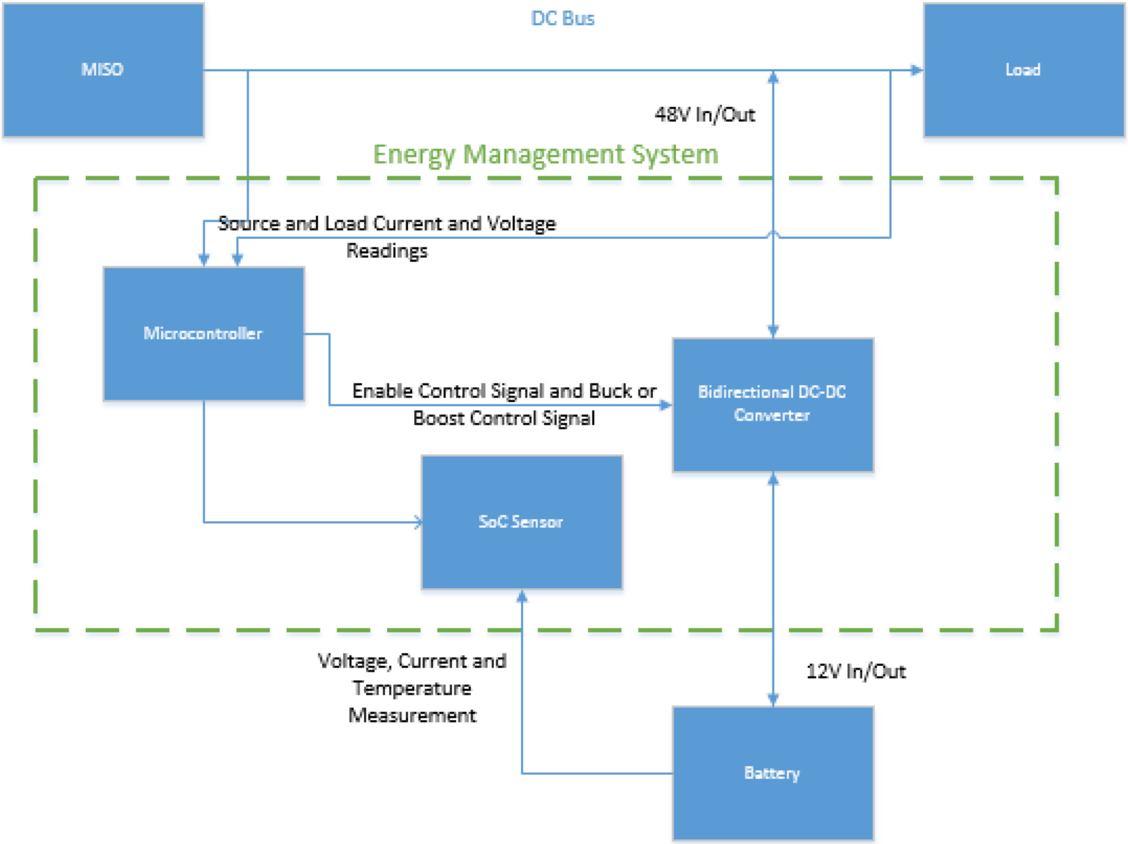


Figure 3-2: Level 1 DC House EMS Block Diagram

Table 3-1 is the EMS system design specifications summary, which details the design specifications laid out in the Level 0 and Level 1 block diagrams (Figure 3-1 and 3-2 respectively), along with basic product design specifications and their explanations [5].

Table 3-1: DC House EMS Design Requirements and Specifications

Marketing Requirements	Engineering Specifications	Justification
1, 2	The system will be comprised of a charge controller, a bidirectional DC-DC power converter, and a microcontroller.	The purpose of the project is to implement a system to control energy and battery charge for the DC house.
3	The DC voltage converter system will have an efficiency of >94%	DC converters should be as efficient as possible to minimize losses. This value was selected by comparing various converters on the market and by aiming for higher efficiency than the previous EMS system.
4	The total system cost should be <$200	This value is derived from the bill of materials developed for initial prototype construction.
5	The entire system should reside in a weather-resistant enclosure.	This will reduce the rate at which electrical systems degrade due to environmental factors.
1	The system will change the flow of charge in real time to meet the load being drawn by the DC house.	In order to operate as efficiently as possible, the charge controller must react to change in power output as quickly as possible.
6	The DC power converter system will convert between 12V and 48V and will be accomplished with a single bidirectional controller.	The source and load run on 48V and the battery bank runs on 12V.
7	The charge controller will provide overcharge, undercharge, and temperature protection.	In order to effectively protect the battery bank, the charge controller must fulfill these requirements.
7	The controller will provide alert for over temperature conditions.	Temperature sensing will make a safer more robust system.
8	The circuit system will be assembled on a replicable, fabricated PCB.	A PCB will make the product less expensive and more easily replaceable.

Marketing Requirements:

1. Should direct current from DC sources (MISO) towards either the load or battery bank depending on load of DC house.
2. The DC-DC converter system should convert DC voltage from 48 to 12V and vice versa.
3. The DC-DC converter system should have a high electrical efficiency.
4. The EMS system should be low cost.
5. The EMS system must be robust and weatherproof.
6. The EMS system should interface with both the MISO controller and the 12V battery bank.
7. Charge controller must protect the battery bank, as well as any connected electrical systems.
8. The EMS system should be replicable, replaceable, and a more “finished product” than the previous EMS prototype.

Chapter 4. Design and Simulation Results

This design of the DC House Energy Management System (EMS) builds on a previous implementation. To improve the system, the two separate DC-DC converters responsible for stepping voltage up or down between the battery and DC bus will be replaced with a single bi-directional converter. The system software will also be altered to utilize the temperature sensing capabilities of the state-of-charge (SOC) sensor. Additionally, the bi-directional converter and the SOC sensor will interface with a microcontroller that will output voltage levels and battery data to a LCD screen. Lastly, a PCB will be fabricated for the system to create a more replicable product. Refer to Figure 3-2 (in the previous chapter) for a Level 1 block diagram to see how all the components interact.

Bidirectional DC-DC Converter

For the bi-directional DC-DC converter, the LTC3871 controller chip was selected. Additionally, this chip is available on a demo board, the DC2348A-B, which meets the interface requirements and power capabilities of the DC House (48V/12V and high current capabilities). Figure 4-1 shows the outline of the demo board as well as connections to the board; Vhigh and GND connect to the 48V DC bus and Vlow and GND connect across the 12V battery. The controls BUCK/BOOST, RUN, and SETCUR are connected to and controlled by the digital output pins of the Arduino microcontroller (discussed later).

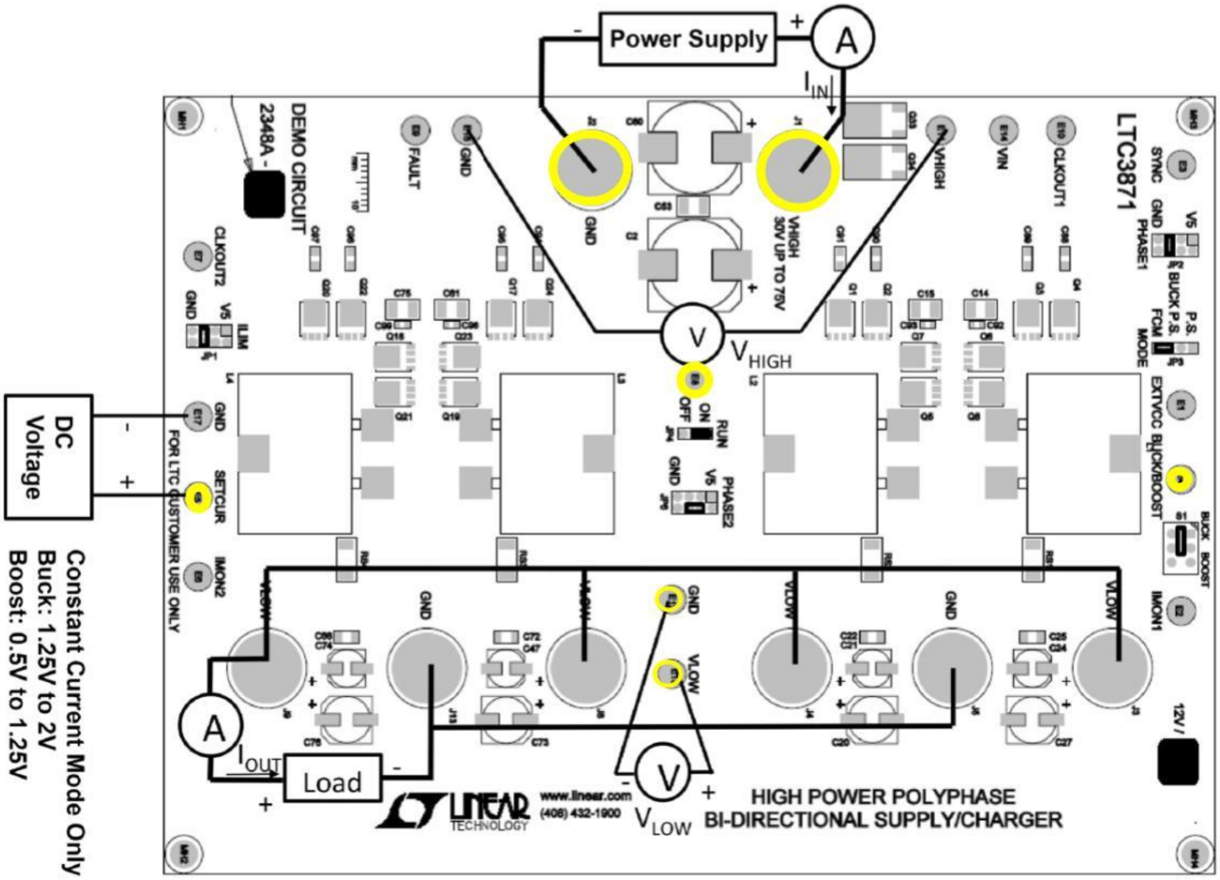


Figure 4-1: Bi-Directional DC-DC Converter Board and Connections

The jumper placements described by the demo manual, shown in Figure 4-1, were used in addition to the previously mentioned three signals to control operation of the converter. After powering on and testing the operation of the board as instructed by the manual, the board was tested using externally applied voltages to confirm the microcontroller would be able to drive the board as expected. A description of the testing of the demo board as well as the modes of operation follows.

Modes of Operation

The converter will need to be run in constant-voltage (CV) boost mode to supply power to the 48V DC bus. In this mode, Vlow (12V) is the input and Vhigh (48V) is the output. Additionally, the BUCK turret is set to 0V and the SETCUR turret is set to GND (0V).

To charge the 12V battery, the converter will need to be run in constant-current (CC) buck mode. Here, Vhigh (48V) is the input and Vlow (12V) is the output. Now the BUCK turret is set to 5V and the SETCUR turret is set to 1.3V by an external resistive divider powered by the microcontroller. The demo manual indicated that for CC buck mode, a 1.25V signal should be applied to the SETCUR turret to start the mode with a minimum current. Testing of the board showed that a 1.27V signal was the minimum needed to enable the board to run and charge the battery at around 2A. Thus, a safe voltage of 1.3V was selected to drive the SETCUR turret. Additionally, test results showed indicated that as the battery voltage drops, the battery draws more current from the converter to charge itself.

A resistor divider network was designed to supply the SETCUR input from the digital input/output (I/O) pins of the Arduino. These I/O pins are either 0V or 5V. Since resistor tolerances could result in a voltage slightly different than ideal values, and since CC buck mode will not run with a SETCUR voltage below 1.27V, the network was designed aiming for a 1.3V output. The following calculations show how the resistor values were determined using 1% resistor tolerances.

$$R_1 := 32.4\ k\Omega \qquad R_2 := 11.5\ k\Omega \qquad V_s := 5\ V$$

$$V_{oMIN} := V_s \cdot \frac{\left(R_2 \cdot 0.99\right)}{\left(R_1 \cdot 1.01\right) + \left(R_2 \cdot 0.99\right)} = 1.291\ V$$

$$V_{oMAX} := V_s \cdot \frac{\left(R_2 \cdot 1.01\right)}{\left(R_1 \cdot 0.99\right) + \left(R_2 \cdot 1.01\right)} = 1.329\ V$$

State-of-Charge (SOC) Sensor

For the SOC sensor, the BQ78412 was chosen as it was the chip used in the previous EMS implementation. This sensor was selected as it was designed for lead acid battery banks, has a capacity of 327 Ahr, and can be controlled by a microcontroller over UART communication [5]. The circuit for the SOC chip was also preserved from the previous implementation of the system. While the state of charge can be approximated using battery voltage and discharge curve for the battery, a SOC chip will provide a more accurate measurement. Figure 4-2 shows this circuit setup for the SOC chip. The nodes TX and RX are connected to the microcontroller, VBAT+ and VBAT- are connected to the terminals of the 12V battery, and Vlow- is the low voltage (12V) bus. The grounded pins of the IC should be connected to the ground of the microcontroller.

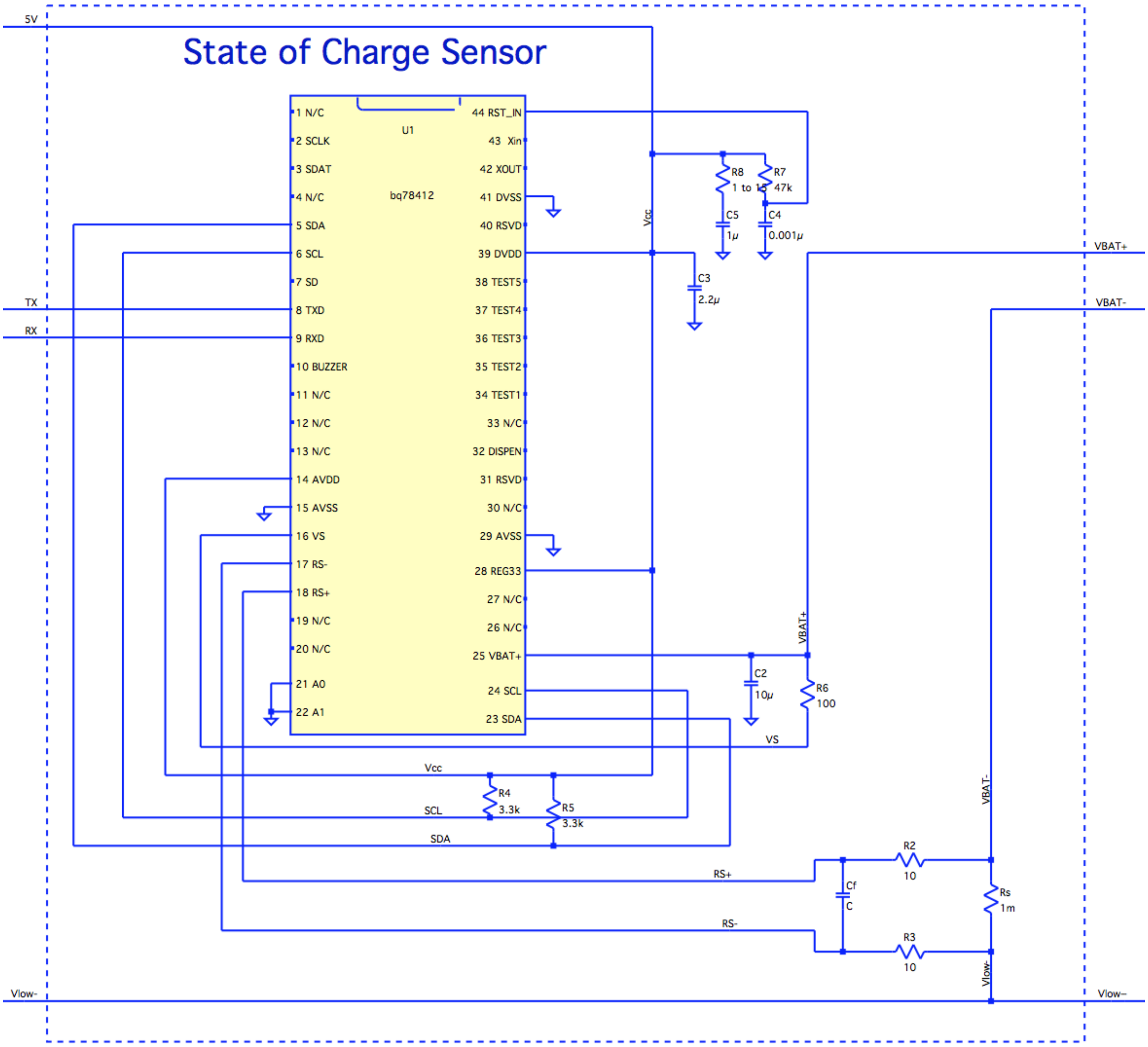


Figure 4-2: Connections to SOC Sensor System

Microcontroller

For the microcontroller, the Arduino Mega2560 was selected. This microcontroller was also used in the previous EMS implementation thus allowing the reuse of a majority of the code that had already been written. The Mega2560 was chosen because it has enough input and output ports, sufficient current driving capabilities, and its widespread use and relatively low cost [5].

Figure 4-3 shows the Mega2560 as well as all of the pins as ports utilized in the design (highlighted in yellow). Additionally, an LCD screen was selected to interface to the Mega2560 through the SDA and SCL pins. This screen indicates the various voltage and SOC readings to the system user.

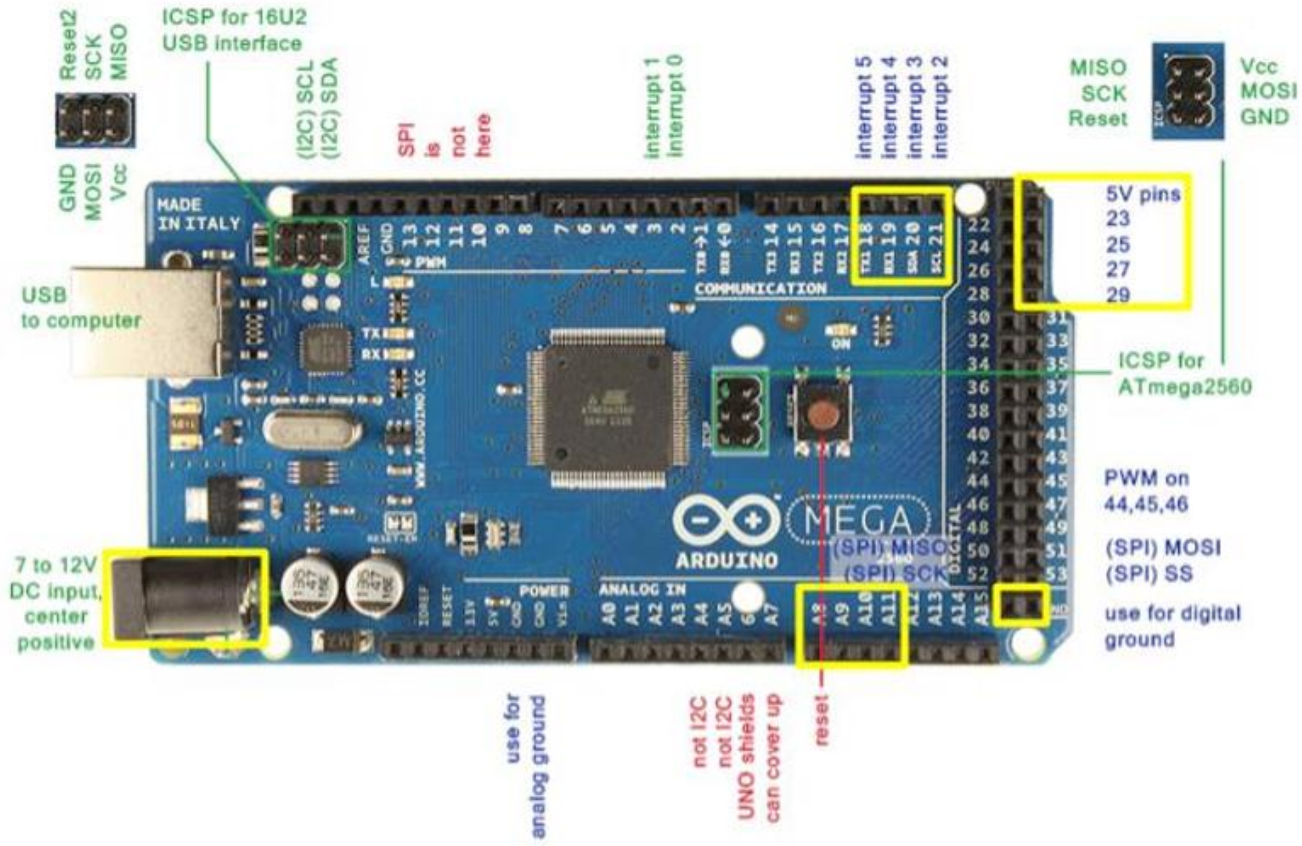


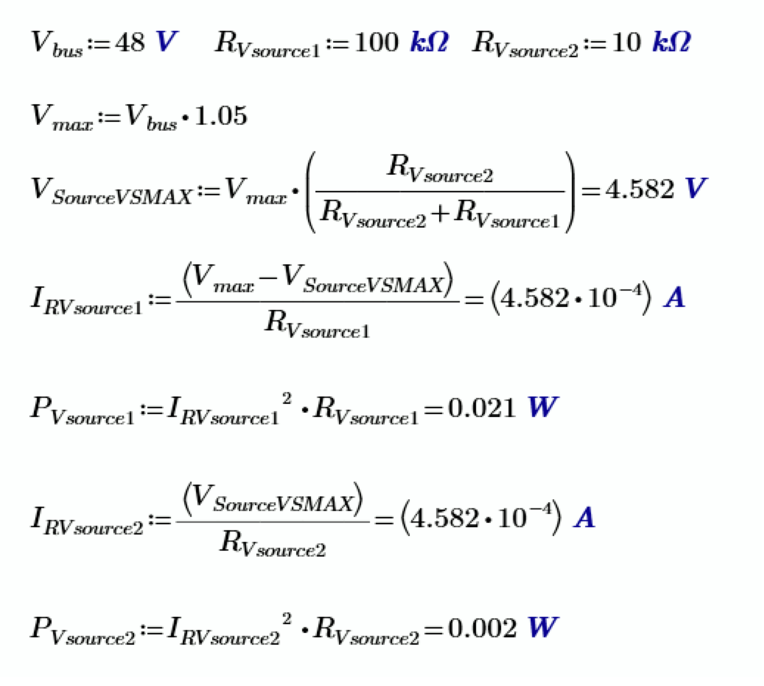
Figure 4-3: Arduino Mega2560 and Connections

Component Selection

Passive components were selected based on the operating conditions of the DC House. Many component values for the SOC (BQ78412) chip were provided in the application notes [7]. Therefore, few components were left to be selected. These component selections, as well as calculations to check the needed voltage and power ratings are detailed as follows. Refer to Appendix A2 for the complete circuit schematic referenced in the component selections and calculations.

Voltage Sensing

Resistors Vsource1 and Vsource2 form an 11:1 voltage divider to allow the microcontroller to monitor the source voltage. The 5.1V zener diode across Vsource2 provides protection for the microcontroller [5]. Ideally, the diode should not conduct. The voltage sense measurements for the load side are taken using the same method as those on the load side, so the following calculations are applicable for both resistive networks.



$$V_{bus} := 48\ \mathbf{V} \qquad R_{Vsource1} := 100\ \mathbf{k\Omega} \qquad R_{Vsource2} := 10\ \mathbf{k\Omega}$$

$$V_{max} := V_{bus} \cdot 1.05$$

$$V_{SourceVSMAX} := V_{max} \cdot \left(\frac{R_{Vsource2}}{R_{Vsource2} + R_{Vsource1}} \right) = 4.582\ \mathbf{V}$$

$$I_{RVsource1} := \frac{\left(V_{max} - V_{SourceVSMAX} \right)}{R_{Vsource1}} = \left(4.582 \cdot 10^{-4} \right)\ \mathbf{A}$$

$$P_{Vsource1} := {I_{RVsource1}}^{2} \cdot R_{Vsource1} = 0.021\ \mathbf{W}$$

$$I_{RVsource2} := \frac{\left(V_{SourceVSMAX} \right)}{R_{Vsource2}} = \left(4.582 \cdot 10^{-4} \right)\ \mathbf{A}$$

$$P_{Vsource2} := {I_{RVsource2}}^{2} \cdot R_{Vsource2} = 0.002\ \mathbf{W}$$

Current Sensing

Sense resistors were chosen as a low complexity method for collecting current measurements. The value of 0.1Ω was selected to allow a readable voltage while not dissipating excessive power [5]. The current sense resistors were sized assuming a maximum load current of 6.25A. At 6.25A, a 100mΩ resistor would dissipate 3.9W. These calculations are shown below.

$$I_{LoadMAX} := 6.25\ \mathbf{A} \qquad R_{CS} := .1\ \mathbf{\Omega}$$

$$V_{CSMAX} := I_{LoadMAX} \cdot R_{CS} = 0.625\ \mathbf{V}$$

$$P_{RcsMAX} := \left(I_{LoadMAX}\right)^2 \cdot R_{CS} = 3.906\ \mathbf{W}$$

Due to the structure of the system, the reading across CSR1 would inherently be a negative voltage. The network formed by R11 and R12 connected to the 5V pin of the Arduino were added to allow a positive voltage measurement to be taken corresponding to the current at the source.

Printed Circuit Board

The SOC sensor system and a majority of the additional components required for the microcontroller to take voltage and current measurements were incorporated into a printed circuit board (PCB) layout. The PCB was designed using Altium Designer 17.0 software and was carefully mapped out to go on top of the Arduino with compatible header pins. Figure 4-4 shows a three-dimensional rendering of the manufactured and soldered PCB.

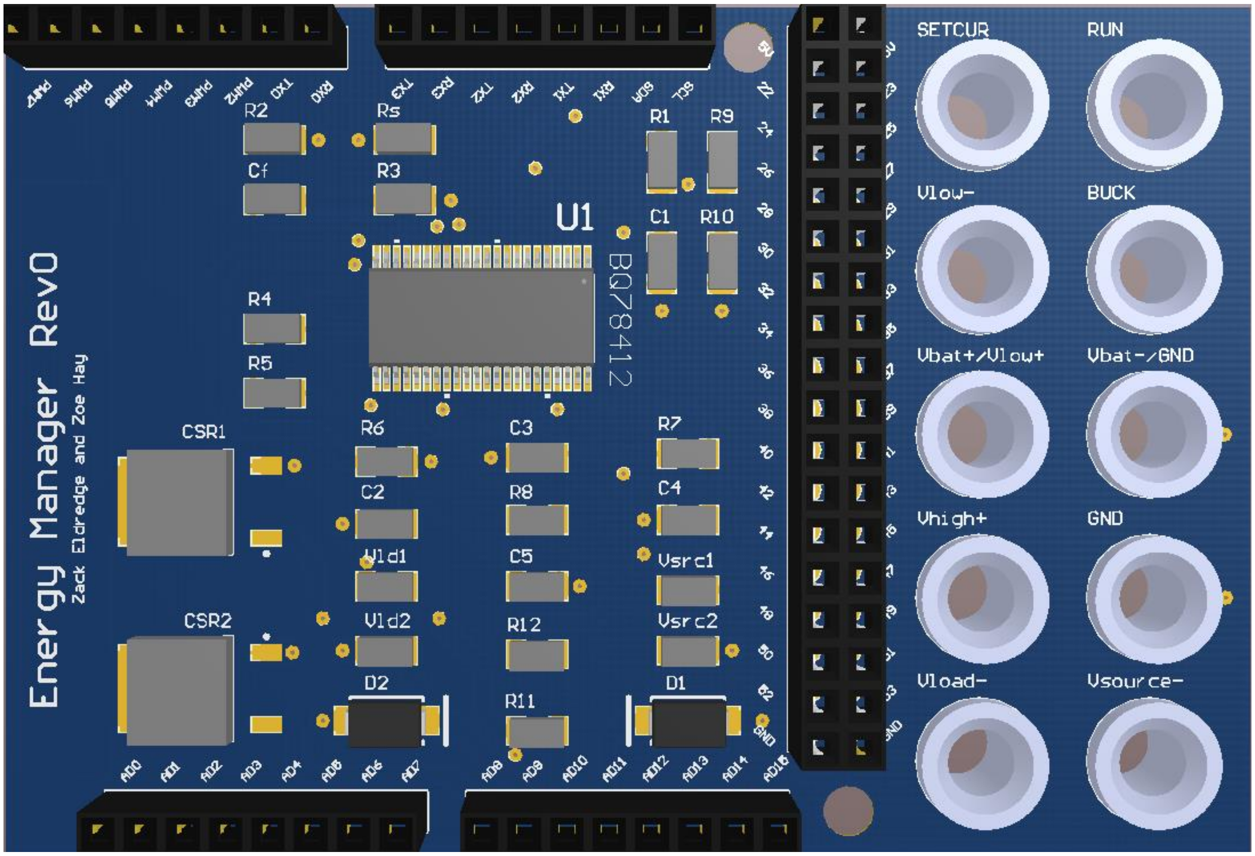


Figure 4-4: 3-D PCB Layout

Chapter 5. Hardware Test and Results

Software Implementation

This version of the EMS for the DC House expands on the software written for the previous implementation [5]. The software is modified to support the changes to the system and to add off-states for the converter. The simple state diagram remains generally the same as the EMS still performs the same function of charging or discharging the battery based on measurements from the system. This state diagram can be seen in Figure 5-1.

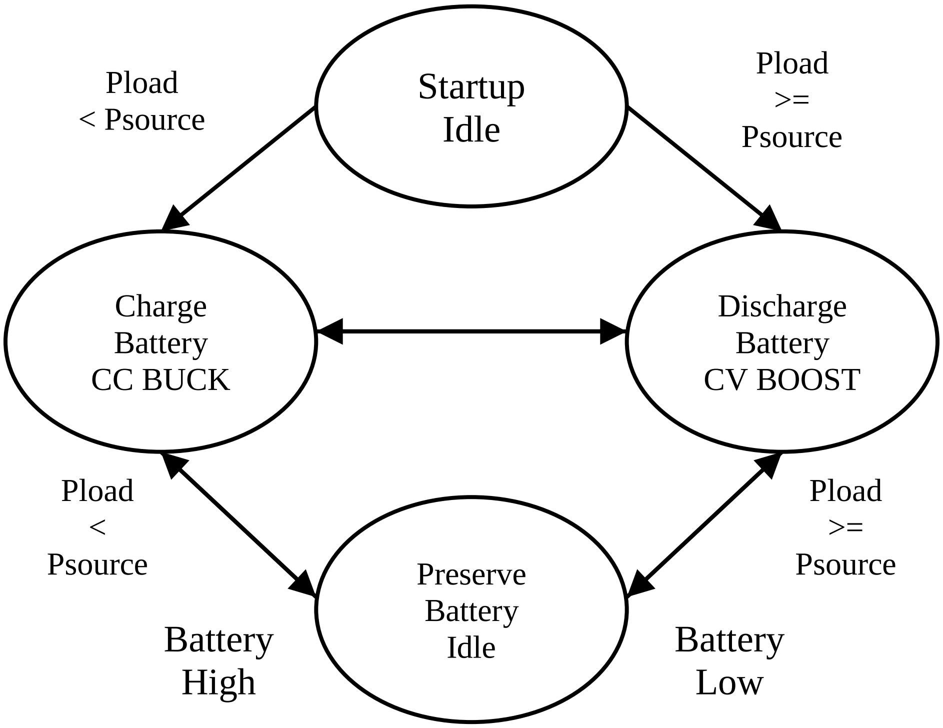


Figure 5-1: Simple State Diagram of Arduino Code

The addition of the bidirectional converter instead of two separate converters requires a different control logic. Instead of signaling relays to control the flow of power, the microcontroller was programmed to provide the RUN, BUCK, and SETCUR signals to the bidirectional converter. Table 5-1 lists the different signal values corresponding to the different modes of the bidirectional converter.

Table 5-1: Signals to Control Bidirectional Converter

Mode	Converter Input	Converter Output	RUN (pin 25)	BUCK (pin 27)	SETCUR (pin 23)
CV BOOST (discharge battery)	Vlow	Vhigh	5V	0V	0V
CC BUCK (charge battery)	Vhigh	Vlow	5V	5V	5V (1.27V after divider)

Additionally, a serial write/read command to read temperature from the SOC sensor was added. The protocol for communicating with the chip was described in the SOC sensor datasheet and formatted based on code from the previous implementation [5][7]. An oscilloscope was used to observe and verify the serial data communication between the Arduino and the SOC sensor.

The code was also modified to write to a four-line LCD display, allowing more information to be shown at once. Furthermore, pushing the external button enables power to the LCD which outputs the system’s measurements. The display is then automatically powered off after a brief period of time to conserve power. Appendix A3 lists the thoroughly commented Arduino code.

Hardware Implementation (PCB and Enclosure)

After the system design and PCB layout were completed, the components were selected and ordered. The parts are listed in the Bill of Materials included in Appendix A4. A large part of the construction of the system required populating the PCB. The Arduino specific header pins provide electrical and mechanical connections between the PCB and the microcontroller to allow the PCB to mount directly onto the microcontroller. Figure 5-2 shows a picture of the populated PCB mounted on the microcontroller.

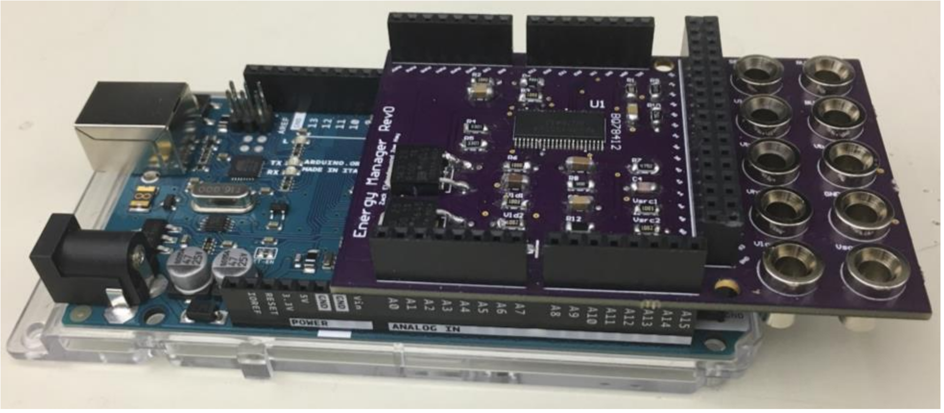


Figure 5-2: PCB and Arduino Microcontroller Setup

Connections to the bidirectional converter and the external button, switch, and display were made with leads and jumpers. A significant part of the design procedure was selecting appropriate connectors. Most of the power connections were made for banana-to-banana leads. The remaining connections, including the signal control connections, were made using banana-to-wire wrap. The LCD display is controlled and connected to the microcontroller via jumpers. An enclosure was selected and holes were drilled for the display, button, and external connectors. The system components were then mounted inside of the protective case. Figures 5-3 and 5-4 depict the constructed enclosure.

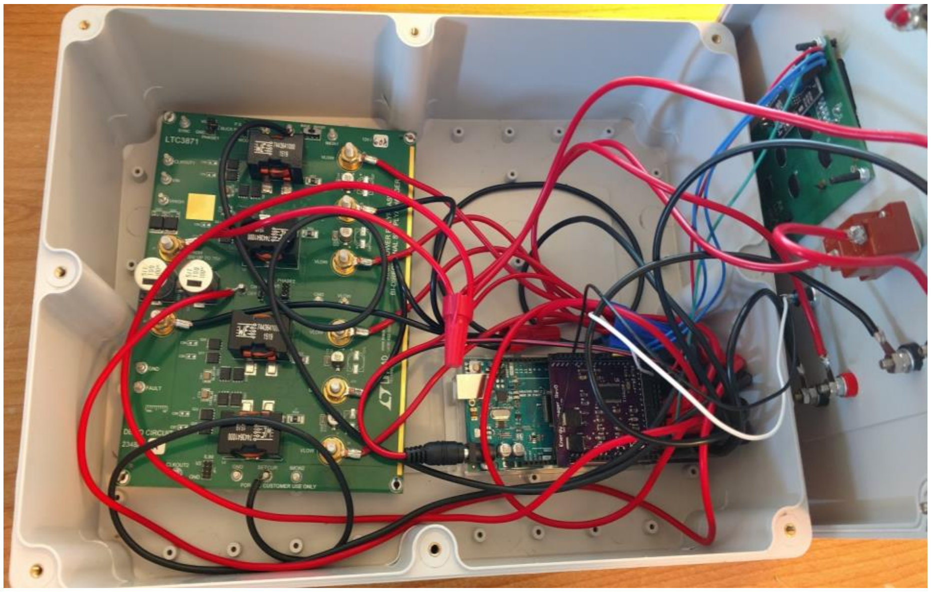


Figure 5-3: Fully Constructed Enclosure (Inside)

Figure 5-4: Fully Constructed Enclosure (Outside)

Bidirectional DC-DC Converter Testing

The Bidirectional DC-DC converter was tested to determine its operating efficiency. For these tests, a DC power supply was connected directly to the turrets of the converter board corresponding to the control signals shown in Table 5-1.

Boost mode will be used when discharging the 12V battery to supply power to the 48V DC bus. This mode was tested with a 12V DC power supply connected to the Vlow side of the converter and an electronic load set to a constant voltage of 48V connected to the Vhigh side. In boost mode, the converter is rated for a maximum output current of 15A [9]. However, when testing in the lab, the DC power supply was only able to supply up to 4.95A at 11.9V. The results are shown in Figure 5-5. This power supply limit corresponds to an output current of only 1.1A, a fraction of the 15A maximum (note that the output current here is on the Vhigh side). As shown by the results, efficiency improves as the output current approaches the full capability of the converter, reaching a maximum of 90% at 1.1A. The significantly higher capability of the converter indicates that a much greater efficiency could be reached when operating at a higher input/output currents exceeding those which could supplied during the lab test.

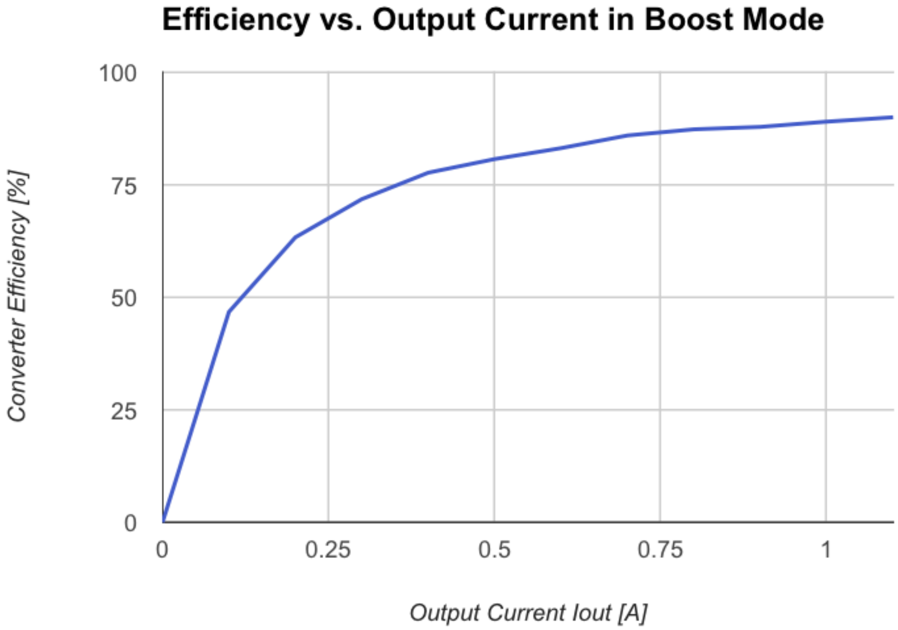


Figure 5-5: Efficiency of the Bidirectional DC-DC Converter Operating in Boost Mode

The converter will be operated in buck mode when power is drawn from the 48V DC bus to charge the 12V battery. This mode was tested with a DC power supply set at 48V connected to Vhigh and an electronic load set at a constant 12V connected to Vlow. In this mode, the output current can be controlled by changing the voltage applied to the SETCUR turret (note that the output current here is on the Vlow side). The valid range for the SETCUR voltage for buck mode operation is from 1.25 to 2V as indicated by the operation manual [9]. Again, due to power limitations in when testing in the lab, the full capabilities of the converter could not be tested. In buck mode, the converter is rated for a maximum output current of 60A. The results are shown in Figure 5-6. While this plot only shows Efficiency vs. Output Current, the corresponding SETCUR voltage is documented in Table 5-2. During testing, the DC power supply was only able to supply up to 1.1A input current at 48V. This corresponded to a maximum efficiency of

88.1%. Again, the converter efficiency improved as output current increased indicating greater efficiency could be observed by testing the converter at a higher power. It was observed that a SETCUR voltage of between 1.29V to 1.33V was the range where the converter operated at 88% efficiency. This corresponds with the design decision to select resistors to set the SETCUR voltage between 1.291V and 1.329V when accounting for worst case resistor values based on their tolerances as discussed in Chapter 4.

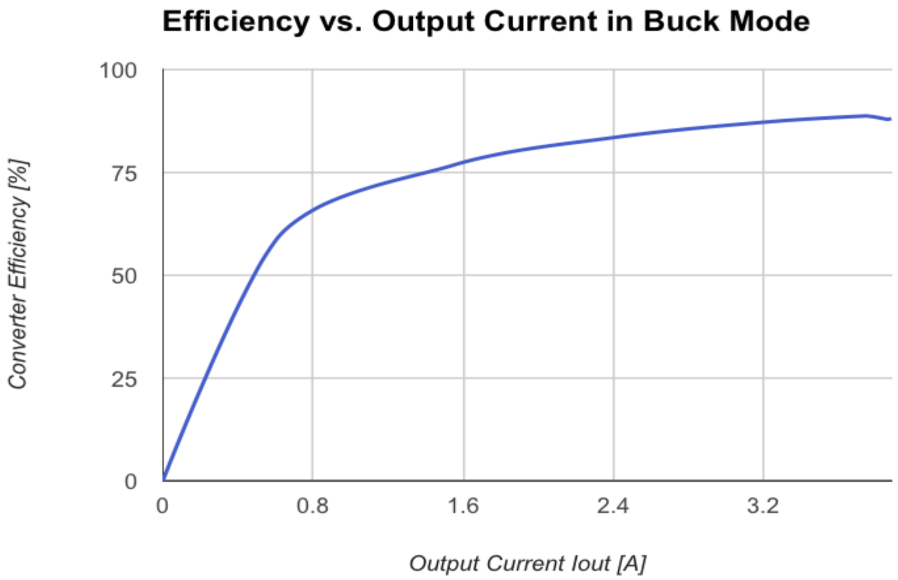


Figure 5-6: Efficiency of the Bidirectional DC-DC Converter Operating in Buck Mode

Table 5-2: SETCUR Voltage vs. Iout and Efficiency for Buck Mode

SETCUR [V]	Iout [A]	Efficiency [%]
1.25	0	0
1.26	0.6	58.36
1.27	1.55	76.79
1.28	2.41	83.54
1.29	3.17	87.09
1.3	3.75	88.74
1.4	3.86	87.91
1.5	3.88	88.11
1.6	3.88	88.11
1.7	3.88	88.11
1.8	3.88	88.11
1.9	3.88	88.11

System Testing

The system was tested using different setups depending on the mode of operation being simulated. Figure 5-7 shows the test setup for when the EMS directs power from the 12V battery to supply power to the 48V DC bus. Solid lines indicate power connections, dashed lines indicate monitoring signals, and arrows indicate the direction of power flow. This indicates the converter will be given control signals corresponding to BOOST mode of operation. This behavior will be induced when Pload > Psource and the battery SOC is greater than 20%. These cases correspond to conditions where the load is drawing more power than the source and the battery is not in danger of deep discharge. As shown in Figure 5-8, the condition of the load drawing more power than is supplied by the source causes a close to 0V signal to be applied to the BUCK turret of the converter and the converter supplies power from the battery to the load by operating in BOOST mode.

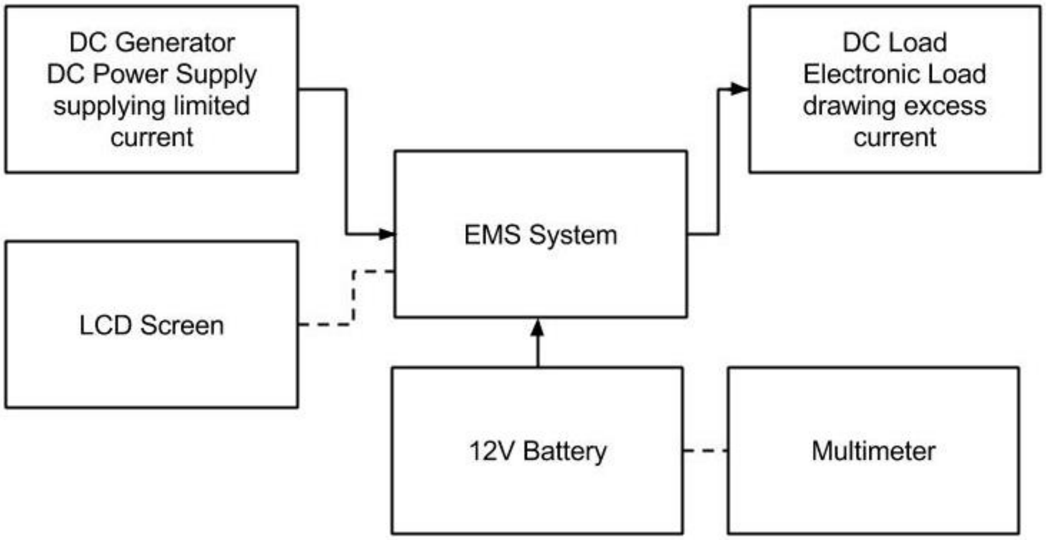


Figure 5-7: Lab Test Setup for BOOST Mode of Operation

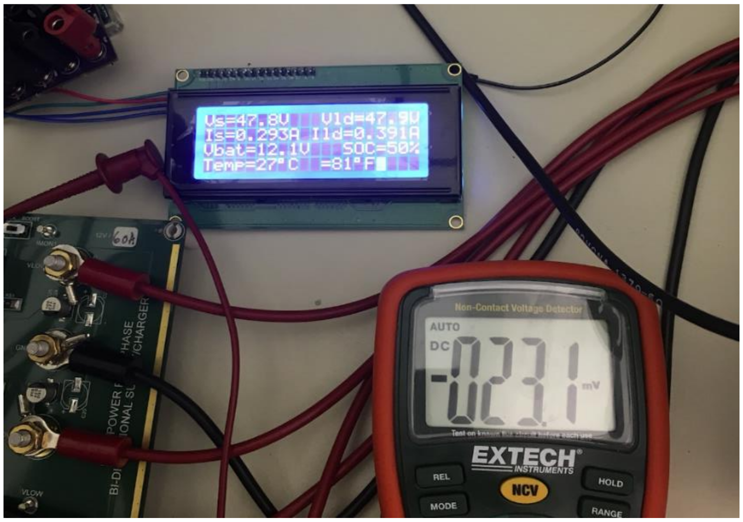


Figure 5-8: LCD Output and BUCK Signal for BOOST Mode of Operation

Figure 5-9 shows the test setup for the condition when the EMS sources power from the 48V bus to charge the 12V battery. This condition corresponds with the converter operating in BUCK mode. The EMS will operate in this mode when Pload < Psource and the battery SOC is less than 80%. These conditions correspond to extra source power being available and the battery being in need of charge. This mode of operation was induced in a lab test by connecting a 48V source and the 12V battery. As shown in Figure 5-10, this condition of the source power being greater than the load power caused a 5V signal to be applied to the BUCK turret of the converter and the system to charge the battery by sourcing current from the DC power supply.

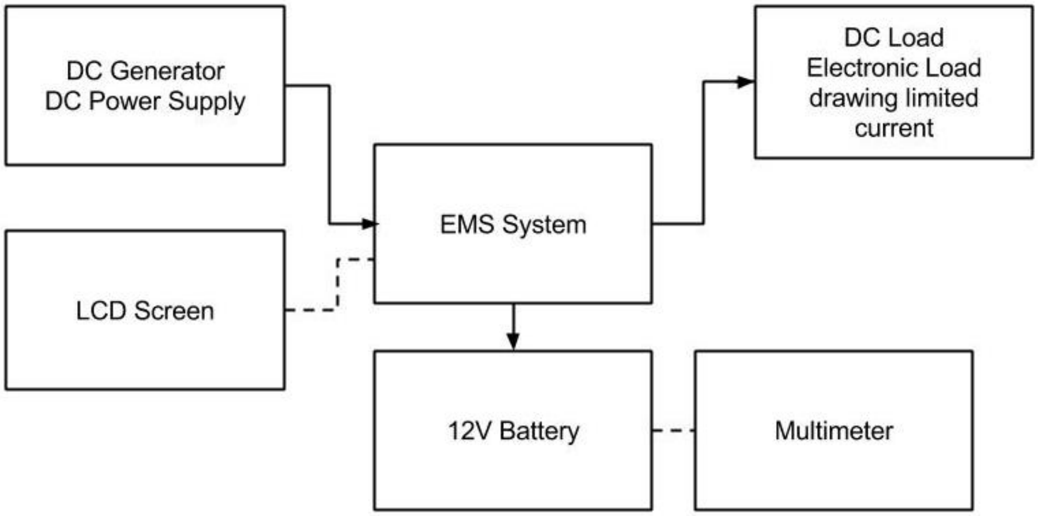


Figure 5-9: Lab Test Setup for BUCK Mode of Operation

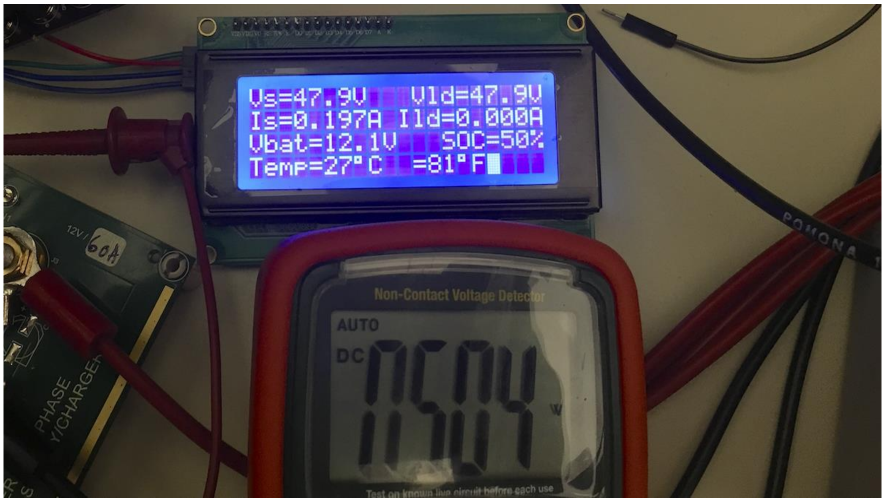


Figure 5-10: LCD Output and BUCK Signal for BUCK Mode of Operation

The power supply and electronic load were adjusted to emulate different conditions and control the mode of the converter. The lab test setup can be seen in Figure 5-11. Figure 5-12 shows the output of the LCD displaying system measurements.

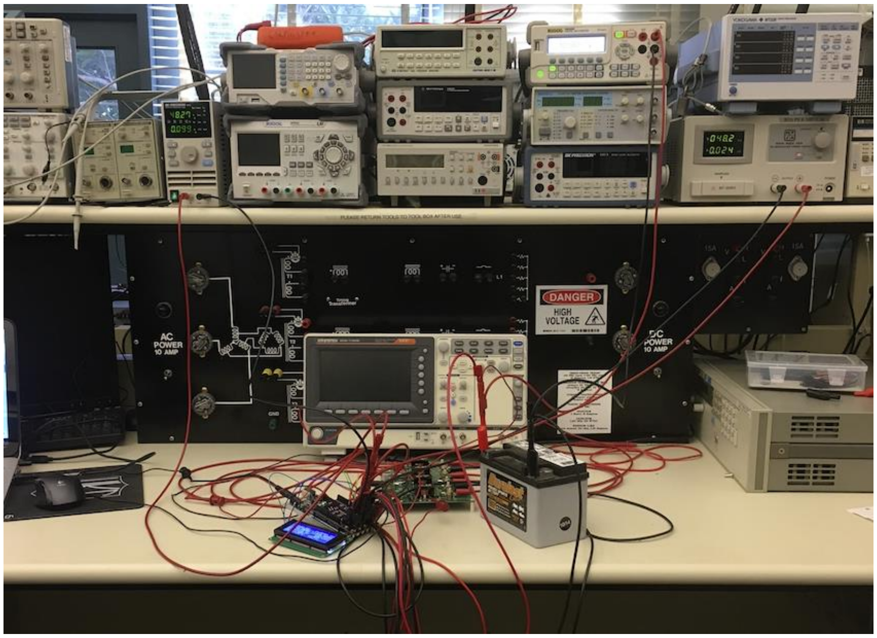


Figure 5-11: Lab Test Setup

Figure 5-12: Display Output During Testing

Table 5-3 shows a summary of the module’s behavior corresponding to the logic implemented in the system’s software. As in the Bidirectional DC-DC Converter Testing section, testing of the system was limited by the power capabilities of the available supplies. Other research for the DC House project (such as in [6]) indicated a maximum load current of 6.25A. As stated in the converter test section, the power capabilities of the DC power supply used to act as the 48V DC bus input to the converter allowed only a maximum output current to the load of 1.1A. More powerful test equipment would be required for testing at more realistic load conditions of at least several amps.

Table 5-3: System Conditions and Behavior

Power	**Battery State of Charge**	**State of Bidirectional Converter**	**Mode**
Pload > Psource	>=80%	Discharge Battery	Constant-Voltage BOOST
Pload <= Psource	>=80%	Don’t Run	OFF
Pload < Psource	<=20%	Charge Battery	Constant-Current BUCK
Pload >= Psource	<=20%	Don’t Run	OFF
Pload > Psource	20% - 80%	Discharge Battery	Constant-Voltage BOOST
Pload <= Psource	20% - 80%	Charge Battery	Constant-Current BUCK

Chapter 6. Conclusion

Test results for the EMS exhibited the behavior desired for control of power flow in a DC House system. Using voltage and current sensing, the EMS charges, discharges, or remains idle depending on the power needs of the system and the SOC of the battery. The LCD outputs these measurements as well as battery voltage, temperature, and SOC readings taken from the SOC sensor. This design of the EMS for the DC House aimed to create a more developed version of a previous proof of concept. The fabrication of a PCB will allow the system to be more replicable and the larger LCD can display more system information. The bidirectional DC-DC converter accomplishes the function previously achieved by two separate converters and the newly revised code utilizes the temperature reading capabilities of the SOC sensor as well as including off states when the system should preserve the battery voltage for more efficient operation.

Some conditions the system might encounter could not be tested on the bench. Observation of the system over time allowing the battery to naturally charge and discharge could provide more relevant data about the system's performance. As discussed in Chapter 5, testing of the converter was limited by the power capabilities of available power supplies. Different equipment could allow analysis of the converter over a wider operating range.

While this project was a new iteration of a previous design for the DC House EMS, another design could make more improvements to the system. It would be beneficial if another redesign of the system could replace the BQ78412 SOC sensor used in this and the previous implementation of the system. Unfortunately, this chip is approaching end of life and will be discontinued. Another issue with the chip was its reliance on serial data communication. When observing the system's measurements during testing, there was significant delay between a change in test conditions and the update of the display. This was due to the slow nature of the serial data communication. A chip with faster communication protocol would allow the system to be more responsive.

Another aspect of the system that requires reconsideration is the overvoltage protection method for the analog input pins of the Arduino Mega which are used to take voltage sense readings. The previous design of the system placed 5.1V Zener diodes across the voltage sensing resistor connected to the Arduino input; when this was implemented in this project, the Zener caused inaccuracy in the voltage read from the divider. This issue might be able to be addressed in code by determining how much voltage corresponds to the current being conducted by the Zener diodes. In the final design of the system, this function could not be reliably implemented and the Zener diodes were removed. Alternatively, a passive low pass filter could be used at the point where the Arduino pin is connected. Because the overvoltage protection is mostly necessary for quick transient spikes, a low pass filter would be capable of providing adequate protection. A subsequent implementation of the EMS should consider how to better protect the Arduino from overvoltage conditions.

A future design of the EMS should consider a different method for taking current measurements. This implementation relies on an analog voltage reading taken by the Arduino from across a current sense resistor which is then processed in code to output a current measurement. Another error observed during testing was caused by the technique of biasing the source current sense analog input pin of the Arduino to 2.5V to bring the negative voltage across the current sense resistor into the positive voltage range. As explained in the report for the previous design of the system, this is necessary because of the 0 to 5V input range of the Arduino analog input pins [5]. This bias voltage sometimes caused a small non-zero current measurement even when no current should have been flowing. While the current measurements obtained from this design were acceptable for the basic functionality of the system, they were not as accurate as those taken directly with a multimeter during testing. Another method such as a dedicated IC or current transducer could provide more accurate readings.

While this implementation of the EMS for the DC House made some improvements to the previously completed proof of concept, future works could produce a more robust system.

References

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Appendix A1 – EMS User's Guide

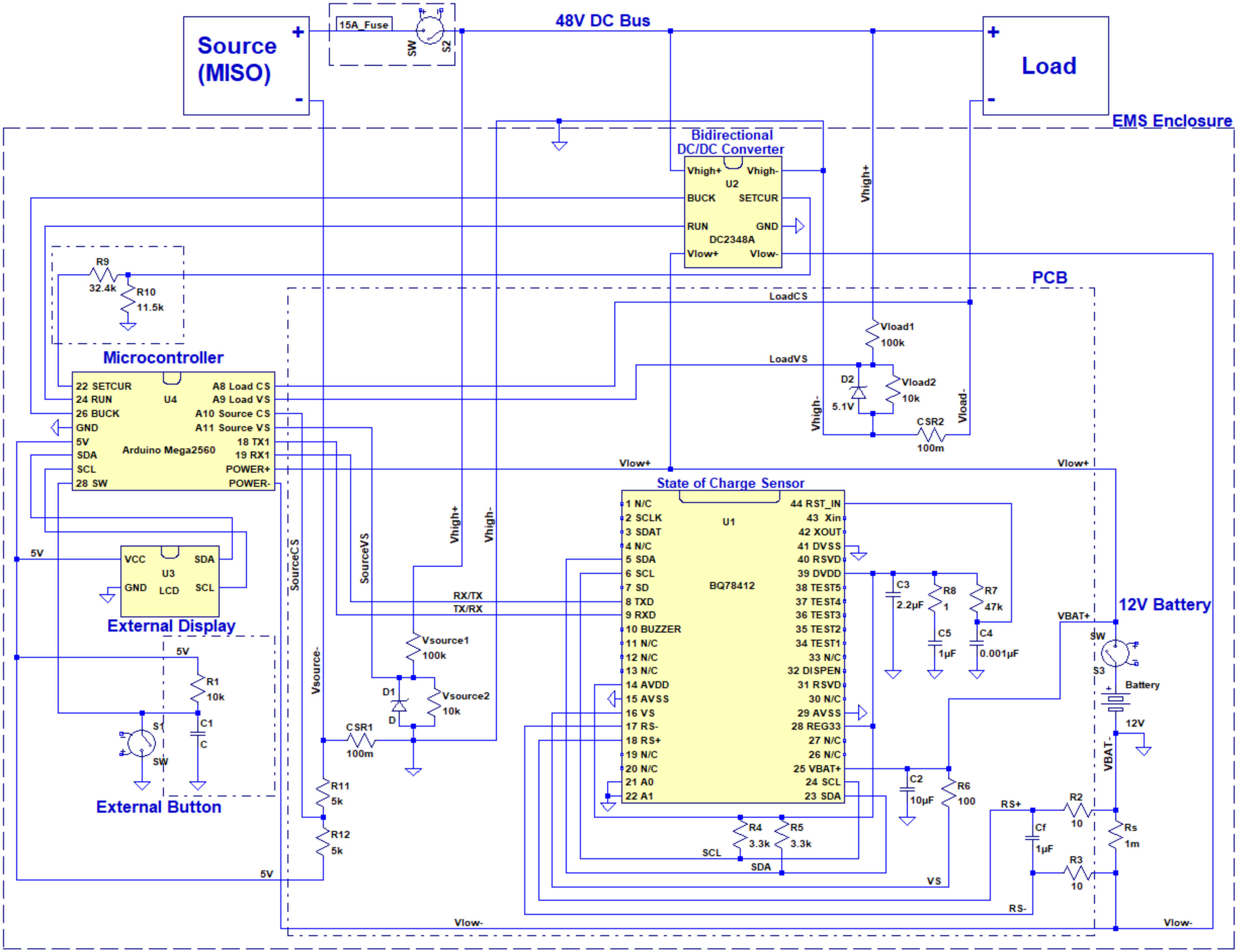
To test or operate the DC House EMS, follow the subsequent procedure.

1) Ensure all leads are disconnected and the main power switches are in the off position.
2) Connect the 12V battery to the battery leads, paying attention to the polarity of the battery.
3) Move the locking toggle switch for the battery to the "ON" position.
4) Connect the source to the source leads, paying attention to the polarity of the source.
5) Move the locking toggle switch for the source to the "ON" position.
6) At this point, the system should be fully powered on.
7) To check the system operation, push down on the momentary switch with the "LCD ON" label. The LCD display should show the pertinent information such as voltage and current for the source, load, and battery. The display should also show the state of charge (SOC) of the battery as a percentage and the temperature inside the enclosure.
8) If all readings are consistent with expected values (such as 48V source and 12V battery), a load may be connected to the device to the load leads, paying attention to the polarity of the load.
9) The device should default to a state in which the battery is charging until it reaches 80% state-of-charge (SOC) or more power is demanded by the load than what can be supplied by the source. At 80% SOC, the battery should either be discharging or the bidirectional converter should shut off, disconnecting the battery from the EMS circuitry entirely.
10) In order to simulate a discharging battery for testing purposes, the locking toggle switch for the source may be moved into the "OFF" position and the load may be hooked up to an electronic load. As long as the battery is greater than 20% SOC, the battery should begin to discharge and supply power to the load; the load voltage should remain around 48V.

11) To power off the system, disconnect any load then move the source power switch then the battery power switch to the “OFF” position.

12) If at any time it is known that both the source and the load are going to supply/demand power respectively, the EMS should have both source and battery power switches toggled “OFF”. This ensures that the EMS won’t run and the battery won’t discharge to save energy and be more efficient. With no source or load, there is no reason to have a battery attached to the system.

Appendix A2 – System Schematic



Appendix A3 – Final System Control Code

```
// EMS DC House Project
// LCD Screen Setup and Test
// Senior Project 2017
// Zack Eldredge and Zoe Hay
// Advisor: Taufik
//--------------------------------------------------------------------//

// Include header files for LCD writing
#include <Wire.h>
#include <LiquidCrystal_I2C.h>

// Set the LCD address to 0x3F for a 20 chars and 4 line display
LiquidCrystal_I2C lcd(0x3F, 20, 4);

//--------------------------------------------------------------------//
//Functions
void writeDisp(double, double, double, double, double);
double toEng(double,double);
//--------------------------------------------------------------------//

//--------------------------------------------------------------------//
//Constants
//actual resistor values for load and source divider, and current
//sense resistor
double rsrc1 = 99700;
double rsrc2 = 10000;
double rld1 = 99700;
double rld2 = 10000;
double resFac1 = ((rsrc1 + rsrc2)/rsrc2);
double resFac2 = ((rld1 + rld2)/rld2);
double csr = 0.100;
//--------------------------------------------------------------------//

//--------------------------------------------------------------------//
//Pin declarations

//Pin connected to momentary switch
int sw1 = 28;
//Pin connected to source voltage divider
int vsrcPin = A11;
//Pin connected to source current resistor
int isrcPin = A10;
//Pin connected to load voltage divider
int vldPin = A9;
//Pin connected to load current resistor
int ildPin = A8;

//Pin connected to RUN turret of converter
int runPin = 24;
//Pin connected to voltage divider connected to SETCUR turret
int setcurPin = 22;
//Pin connected to BUCK turret of converter
```

```
int buckPin = 26;
//Pin connected to LCD Power (5V)
int lcd_power = 30;
//-----------------------------------------------------------------------//

//-----------------------------------------------------------------------//
//Variables
//Variable for reading pin status
int val = 0;
//Variable for reading source voltage in counts
double vsrcRaw = 0;
//Variable for reading source current in counts
double isrcRaw = 0;
//Variable for reading load voltage in counts
double vldRaw = 0;
//Variable for reading load current in counts
double ildRaw = 0;
//Variable for storing source voltage
double vsrc = 0;
//Variable for storing source current
double isrc = 0;

//Variable for storing load voltage
double vld = 0;
//Variable for storing load current
double ild = 0;
//Variable for storing source power
double psrc = 0;
//Variable for storing load power
double pld = 0;
//Variable for reading battery voltage
double vbat = 0;
//Variable for reading battery state of charge
double soc = 0;
//Variable for storing temperature values
double temperature_c = 0;
double temperature_f = 0;
//-----------------------------------------------------------------------//

//-----------------------------------------------------------------------//
//I/O Setup
void setup()
{
  pinMode(runPin, OUTPUT);
  pinMode(setcurPin, OUTPUT);
  pinMode(buckPin, OUTPUT);
  pinMode(lcd_power, OUTPUT);

  pinMode(sw1, INPUT);

  Serial.begin(9600);
  Serial.flush();

  Serial2.begin(9600);
```

```
  Serial2.flush();

  analogReference(DEFAULT);

  //Init battery to charge state and screen off
  digitalWrite(buckPin, HIGH);
  digitalWrite(setcurPin, HIGH);
  digitalWrite(runPin, HIGH);
  digitalWrite(lcd_power, LOW);
}
//-----------------------------------------------------------------------//

//-----------------------------------------------------------------------//
//Main loop
void loop()
{
  //Read voltages from divider, current sense resistors
  vsrcRaw = analogRead(vsrcPin);
  isrcRaw = analogRead(isrcPin);
  vldRaw = analogRead(vldPin);
  ildRaw = analogRead(ildPin);

  //Read BQ status
  vbat = bqRead(1);
  soc = bqRead(2);
  temperature_c = bqRead(3);

  //Convert temp to Farenheit
  temperature_f = temperature_c * 1.8 + 32;

  //Convert counts to eng units
  vsrc = toEng(vsrcRaw, resFac1);
  isrc = (2.5 - toEng(isrcRaw, 1)) *2/csr;
  vld = toEng(vldRaw , resFac2);
  ild = (toEng(ildRaw, 1)) *2/csr;

  //Calculate power
  psrc = vsrc * isrc;
  pld = vld * ild;

  //Control converter
  //If battery is in danger of overcharge
  if(soc >= 80)
  {
    //If more power is required by the load
    if(pld > psrc)
    {
      //Allow battery to discharge only (Constant Voltage BOOST Mode)
      digitalWrite(buckPin, LOW);
      digitalWrite(setcurPin, LOW);
      digitalWrite(runPin, HIGH);
    }
    //Else do nothing and turn off converter
    else
```

```
    {
      //Turn off Bi-Directional Converter
      digitalWrite(buckPin, LOW);
      digitalWrite(setcurPin, LOW);
      digitalWrite(runPin, LOW);
    }
  }

  //If battery is in danger of deep discharge
  else if(soc <= 20)
  {
    //If excess power is supplied than required by the load
    if(pld<psrc)
    {
      //Allow battery to charge only (Constant Current BUCK Mode)
      digitalWrite(buckPin, HIGH);
      digitalWrite(setcurPin, HIGH);
      digitalWrite(runPin, HIGH);
    }
    //Else do nothing and turn off converter
    else
    {
      //Turn off Bi-Directional Converter
      digitalWrite(buckPin, LOW);
      digitalWrite(setcurPin, LOW);
      digitalWrite(runPin, LOW);
    }
  }

  //If battery SOC in safe range (20%<SOC<80%)
  else
  {
    //Assume battery initialized to charge state
    //If input voltage drops, or the load requires more power, discharge
battery
    if((0.9*pld) > psrc)
    {
      //Allow battery to discharge only (Constant Voltage BOOST Mode)
      digitalWrite(buckPin, LOW);
      digitalWrite(setcurPin, LOW);
      digitalWrite(runPin, HIGH);
    }
    //otherwise, default to charging the battery when in good SOC zone
    else
    {
      //Allow battery to charge only (Constant Current BUCK Mode)
      digitalWrite(buckPin, HIGH);
      digitalWrite(setcurPin, HIGH);
      digitalWrite(runPin, HIGH);
    }
  }

  // Determine state of display momentary switch
  val = digitalRead(sw1);
```

```
  // val = 0;

  // If the button is not pressed, clear the screen
  if(val == HIGH)
  {
    //Turn LCD Screen Off
    digitalWrite(lcd_power, LOW);
  }
  //If the button is pressed, display information
  else
  {
    //Push value indicated by display count to display
    writeDisp(vld, vsrc, vbat, soc, temperature_c);
  }
}
//------------------------------------------------------------------------//

//------------------------------------------------------------------------//
//Functions
//Writes values to display
void writeDisp(double vld, double vsrc, double vbat, double soc, double
temperature_c)
{
  digitalWrite(lcd_power, HIGH);

  // initialize the LCD
  lcd.begin();
  lcd.blink();
  lcd.cursor();

  // Turn on the blacklight and print output
  lcd.backlight();
  lcd.print("Vs=");
  lcd.print(vsrc,1);
  lcd.print("V   Vld=");
  lcd.print(vld,1);
  lcd.print("V");
  lcd.setCursor(0, 1);
  lcd.print("Is=");
  lcd.print(isrc,3);
  lcd.print("A Ild=");
  lcd.print(ild,3);
  lcd.print("A");
  lcd.setCursor(0, 2);
  lcd.print("Vbat=");
  lcd.print(vbat,1);
  lcd.print("V   SOC=");
  lcd.print(soc,0);
  lcd.print("%");
  lcd.setCursor(0, 3);
  lcd.print("Temp=");
  lcd.print(temperature_c,0);
  lcd.print((char)223);
  lcd.print("C  =");
```

```
  lcd.print(temperature_f,0);
  lcd.print((char)223);
  lcd.print("F");
  delay(10000);
  digitalWrite(lcd_power, LOW);
}


double bqRead(int cmd)
{
  // Declare variables
  char msgChar;
  char temp;
  byte msgByte;
  int timer = 0;
  byte message[10] = {0};
  double data = 0;
  int counter = 0;
  if(cmd == 1)
  {
    // Query board for battery voltage
    Serial2.write(B11111111);
    Serial2.write(B00010110);
    Serial2.write(B00000100);
    Serial2.write(B00000000);
    Serial2.write(B00000001);
    Serial2.write(B00000000);
    Serial2.write(B00010011);
  }
  else if(cmd == 2)
  {
    // Query board for SOC
    Serial2.write(B11111111);
    Serial2.write(B00010110);
    Serial2.write(B00010110);
    Serial2.write(B00000000);
    Serial2.write(B00000001);
    Serial2.write(B00000000);
    Serial2.write(B00000001);
  }
  else if(cmd == 3)
  {
    //Queary board for temperature
    Serial2.write(B11111111);
    Serial2.write(B00010110);
    Serial2.write(B00000010);
    Serial2.write(B00000000);
    Serial2.write(B00000001);
    Serial2.write(B00000000);
    Serial2.write(B00010101);
  }

  //Timed loop reads serial information until no byte is received for
10000 counts
```

```
  while(timer < 10000)
  {
    // If serial data becomes available from the chip
    if (Serial2.available() == 1)
    {
      //Assign read data to msgByte and msgChar
      msgByte = Serial2.read();
      msgChar = msgByte;

      //Append byte to byte array
      message[counter] = msgByte;

      //reset timer and increment byte counter
      timer = 0;
      counter++;
    }
    else
    {
      //increment timer
      timer ++;
    }
  }

  //Run parseArray function to obtain formatted double from data bytes
  data = parseArray(2,3,message);
    if(cmd == 1)
    {
      data = data / 1000;
    }
    return data;
}


//Function to parse byte array and output int value
double parseArray(int lsb, int msb, byte message[])
{
  //counter begins at least significant bit
  int i = lsb;

  //byte counter initialized to zero
  int bytepos = 0;

  //returned result
  double result = 0;

  //Loop completed for all bits lsb-msb
  while(i <= msb)
  {
    //Take result and add weighted byte value
    result = result + (message[i] * pow(256,bytepos));
    //increment byte position and loop counter
    bytepos++;
    i++;
  }
```

```
  return result;
}


//Function to convert from counts to engineering units
double toEng(double counts,double resFac)
{
  double result = 0;
  double temp = 0;
  double divFac = 0.0048828125; // 5/1024

  //Convert counts to voltage assuming 10 bit input range, 5 volt
reference voltage
  temp = counts * divFac;
  result = temp * resFac;
  return result;
}
```

Appendix A4 – Bill of Materials

Component Type	**Reference Designator**	**Part Number/Description**	**Quantity**	**Unit Price**	**Total Cost**
Controller	U4	Arduino Mega2560 Microcontroller	1	45.950	$45.950
DC-DC Converter	U2	DC2348A-B LTC3871HLXE#PBF Demo Board | Bidirectional Controller	1	370.000	$370.000
State of Charge Sensor	U1	IC BATT GAS GAUGE DISP 44HTSSOP bq78412	1	7.889	$7.889
Display	U3	Frentaly IIC/I2C/TWI 2004 Serial LCD Module	1	12.750	$12.750
System Resistors	Vload1, Vsource1	100k Ohm ±1% 0.25W, 1/4W Chip Resistor 1206 (3216 Metric)	2	0.100	$0.200
	Vload2, Vsource2, R1	10k Ohm ±1% 0.25W, 1/4W Chip Resistor 1206 (3216 Metric)	3	0.100	$0.300
	CSR1, CSR2	0.1 Ohm ±1% 25W Chip Resistor TO-252-3, DPak (2 Leads + Tab), Current Sense	2	2.613	$5.226
	R11, R12	5k Ohm ±0.1% 0.25W, 1/4W Chip Resistor 1206 (3216 Metric)	2	0.402	$0.804
	RSETCUR1 R9	32.4k Ohm ±1% 0.25W, 1/4W Chip Resistor 1206 (3216 Metric)	1	0.100	$0.100
	RSETCUR2 R10	11.5k Ohm ±1% 0.25W, 1/4W Chip Resistor 1206 (3216 Metric)	1	0.100	$0.100
Resistors For SOC	R8	1 Ohm ±1% 0.25W, 1/4W Chip Resistor 1206 (3216 Metric)	1	0.100	$0.100
	R7	47k Ohm ±1% 0.25W, 1/4W Chip Resistor 1206 (3216 Metric)	1	0.100	$0.100
	R6	100 Ohm ±1% 0.25W, 1/4W Chip Resistor 1206 (3216 Metric)	1	0.100	$0.100
	R4, R5	3.3k Ohm ±1% 0.25W, 1/4W Chip Resistor 1206 (3216 Metric)	2	0.060	$0.120
	R2, R3	10 Ohm ±1% 0.25W, 1/4W Chip Resistor 1206 (3216 Metric)	2	0.100	$0.200
	Rs	0.001 Ohm ±1% 1W Chip Resistor 1206 (3216 Metric) Current Sense	1	0.650	$0.650
Capacitors For SOC	C2	10μF ±10% 25V Ceramic Capacitor X5R 1206 (3216 Metric)	1	0.290	$0.290
	C3	2.2μF ±10% 25V Ceramic Capacitor X7R 1206 (3216 Metric)	1	0.230	$0.230
	C4	1pF ±0.25pF 50V Ceramic Capacitor C0G, NP0 1206 (3216 Metric)	1	0.160	$0.160
	Cf, C5, C1	1μF ±5% 25V Ceramic Capacitor X7R 1206 (3216 Metric)	3	0.248	$0.744
PCB Connectors	SETCUR, RUN, Vlow-, BUCK, Vbat+/Vlow+, Vbat-/GND, Vhigh+, GND, Vload-, Vsource-	Non-Insulated .350" Banana Jack Connector Standard Banana Solder	10	0.589	$5.890
	Header Pins	Mega protoshield for Arduino	1	14.950	$14.950
	Power Jack Connector	MassMall 10pack 10 inch(30cm) 2.1 x 5.5mm DC Power Pigtail MALE	1	0.655	$0.655
Enclosure and Connectors	Enclosure	Waterproof Plastic Sealed Enclosure Case Junction Box 320x240x110mm	1	29.470	$29.470
	Banana Connector	uxcell 10Pcs Red Black Speaker 4mm Cable Male Banana Connector		0.388	$0.000
	Banana Binding Post	CESS 4mm Terminal Binding Post Power Audio Amplifier Plug Banana Jack Socket	6	0.599	$3.594
Momentary Switch	SW1	Pushbutton Switch SPST-NO Keyswitch Through Hole	1	0.820	$0.820
Circuit Breaker		CIR BRKR THRM 15A 250VAC	1	2.270	$2.270
Main Power Switch	SW2, SW3	SWITCH TOGGLE SPST 15A 125V	1	11.830	$11.830
PCB Fabrication	PCB	OSH Park 3.11x2.11 inch 2 layer board	1	10.933	$10.933
TOTAL					**$515.492**

Appendix A5 – Timeline of Tasks and Milestones

Winter Quarter 2017

Task Name	January				February				March		
	9	16	23	30	6	13	20	27	6	13	20
Select Controller Chip		🟥	🟥								
Select and Learn Layout Software		🟥	🟥	🟥	🟥	🟥	🟥				
Select other Components and Design			🟥	🟥	🟥	🟥					
Acquire/Purchase Components					🟥	🟥	🟥	🟥			
Board Layout Design								🟥	🟥	🟥	🟥
Write Report	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
BOM										🟥	🟥

Spring Quarter 2017

Task Name	April				May					June	
	3	10	17	24	1	8	15	22	29	5	12
System Design and Simulation	🟥	🟥	🟥	🟥							
Hardware Construction and Testing					🟥	🟥	🟥	🟥	🟥	🟥	
Test Converter					🟥	🟥					
Test PCB/Controller						🟥	🟥	🟥			
Test Complete System								🟥	🟥	🟥	
Encase Sytsem in Enclosure										🟥	🟥
Write Report	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Senior Project Demo											🟥

Appendix A6 – Analysis of Senior Project

Project Title: Energy Management System for the DC House

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1) Summary of Functional Requirements

   The purpose of this design was to supervise the power flow for the DC House project, a project which aims to bring electricity to remote locations and encourage use of renewable energy sources. The Energy Management System of the DC House will control the flow of power based on energy available from the DC generators, the state of charge of the battery, and the energy requirements of the DC house load. The EMS will monitor the conditions in the DC system and charge the battery from the DC bus, discharge the battery to the load, or remain idle.

2) Primary Constraints

   The system must be designed to be compatible with the rest of the DC House power system. It must operate safely and reliably. It must be designed to improve performance and minimize cost. The project should also be easily reproducible and well documented for future research.

3) Economic

   a) What economic impacts result?

    i) Human Capital: The goal of the DC House is to bring electricity to rural areas of the world. Access to electricity will improve people's living conditions and increase economic potential.

    ii) Financial Capital: Increased standard of living will potentially foster economic development. Additionally, the application of DC systems should result in greater efficiency and lower power costs.

    iii) Natural Capital: The electrical components of the system will add material costs. The DC House system is built to run off renewable energy. The adoption of more DC systems could allow transition away from nonrenewable energy resource.

    iv) Costs/Timing: The costs of the project are in the design and implementation of the system. Over time, the cost of building a full DC House system should decrease with future iterations. The DC House is built to last reliably for as long as possible. This product should not require frequent update or redesign. As the DC House project is ongoing, however, new implementations could update the design.

4) If Manufactured on a Commercial Basis

   In the initial stages of implementing DC Houses, converters for several houses will be fabricated. For a 150 W house, the cost for the whole DC House system has been estimated to be from \$750 to \$1000. The humanitarian objective of the DC House project does not prioritize direct profit from the sales of the system. The use of renewable energy sources in the DC system allows it to be self-sustaining once implemented.

5) Environmental

   a) What environmental impacts are associated with manufacturing or use?

Environmental impacts may be associated with the manufacturing of components in this project.

- b) Which natural resources and ecosystem services does the project use (directly and indirectly), improve, or harm?

  As a part of the DC House project, this project can support the conservation of nonrenewable energy sources and spread the use of renewable energy. The DC House project is designed to use resources such as hydro and solar power.

- c) How does the project impact other species?

  Indirectly, as a part of the DC House project and future DC system implementations, this endeavor could reduce environmental damage and threat to species from other nonrenewable energy sources.

6) Manufacturability
   - a) Describe any issues or challenges associated with manufacturing.

     The design will need to be surface mount soldered. For testing and initial use, this will be done by hand. The project will be designed with the goal of affordable manufacturability.

7) Sustainability
   - a) Describe any issues or challenges associated with maintaining the completed device.

     The device should have a long lifetime as it is designed for rural areas. Care should be taken to select components with long lifetimes and proper ratings to ensure longevity.
   - b) Describe how the product impacts the sustainable use of resources.

     The development of DC based systems can encourage the use of sustainable sources of energy.
   - c) Describe any upgrades that would improve the design of the project.

Future development in electrical devices and power electronics could improve the efficiency in the design or allow better implementations that are smaller and lower in cost.

   d) Describe any issues or challenges associated with upgrading the design.

      As a part of the DC House project, this design should be upgradable while following standard voltage levels used by other DC houses that could be interconnected in the future.

8) Ethical
   a) Ethical implications relating to the design, manufacture, use, or misuse of the project:
      i) The primary positive ethical implication of this product is the people who will eventually live in a DC house. These people will benefit from having access to a reliable energy source if it wasn’t previously available. Another benefit is that the DC house will be a renewable and clean (no emissions) source of energy. Misuse of the product could result in electrical shock and possibly bodily harm. Necessary protocols and warnings will be implemented to prevent accidents from misuse. Per the IEEE code of ethics, our product will be tested to guarantee that performance specifications are met with absolute certainty, under both ideal and non-ideal conditions.
9) Health and Safety
   a) Health and safety concerns associated with design, manufacture or use of the project.

      Electrical systems can pose a safety risk. The high voltage nature of the project indicates safety and fault protection should be a key concern. The spread of energy to remote locations should have a positive effect on health and living conditions.
10) Societal and Political

a) Social and political issues associated with design, manufacture and use: The basis of the DC House project has positive social intentions to connect people and improve quality of life. The spread of renewable energy associated with DC powered houses in general will have wider positive social and political effects.

b) Who does the project impact? Who are the direct and indirect stakeholders? How are they affected?

   The priority of the DC House project is to bring electricity to rural areas. The team working on the DC House will be affected by the potential use of the project and research materials.

11) Development

a) New tools or techniques, used for either development or analysis that were learned during the course of this project:

   The completion of this project will require an understanding of power flow and programming knowledge for interfacing with the state of charge sensor. Implementation will also require knowledge of PCB design and layout as well as surface mount soldering.