ECE 445

Spring 2020

Design Document

Hip Hop Xpress: Power Management System for Converted School Bus

Team 61

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1. Introduction

Objective

The School of Architecture and the School of Music at the University of Illinois at Urbana-Champaign converted a school bus that will serve as a mobile educational platform to teach children about STEM through hip hop and music [1]. This bus will contain musical equipment, such as stereos and mixing tables, various LEDs and educational mediums. For this bus to run all of these electronics while the bus engineer is off, a battery reserve must be implemented. This bus must attract people with music and lights, while also being environmentally friendly. In order to accomplish this the electronics on the bus must be battery-driven and work for an extended period of time without running the engine.

Dr. William Paterson, who is taking lead on this project, approached the ECE department of the University of Illinois for expertise to help build the power system for this bus.
Our goal is to develop a working model of a power system that can be scalable to power the school bus. We will be focusing on creating a custom battery management system and data management subsystem. Due to the electronics on the bus having a large power load we will be using lithium ion batteries. These battery packs will be managed using our custom battery management system (BMS) PCB. This BMS will have the ability to charge the batteries from a solar array. The BMS will also be monitoring voltage, current and temperatures from the battery packs.

Background

The Hip Hop Xpress Bus will be driving to neighborhoods that consist primarily of low-income homes [1]. Children of these neighborhoods may not have access to musical equipment nor do schools in these neighborhoods have enough resources to provide an enriching musical education. This school bus will host numerous activities and classes to teach students how to produce and create music through STEM activities, fostering a sense of community and creativity in the neighborhood.

Although many teams on this project are creating activities and visuals, they do not have access to power such electronics. Our senior design team will be tackling the issue of power management through our power system design.

A power system that will take in solar is essential to make the equipment on the bus work and also be environmentally friendly. Another main focus is to keep our system as safe as possible. Taking inspiration from research papers to develop a safe system, we will be implementing a BMS that continuously check voltage, current and temperature values of the batteries and will also have isolation between the batteries and the rest of our system (2), (3). By checking these values the system will be able to shut off if any of these values exceed the safe values.

High-Level Requirements

- The battery management system will have the ability to charge the batteries through solar power and ensure that the batteries do not overcharge, keeping current average at 500 mA +/- 20% and maximum peak current less than 1 A +/- 20%.
- The battery management system will shut off if current (6 A), voltage (3v-4.2v), or temperature (45° C) measured on each battery exceed certain values that are unsafe.
- When discharging, current from battery array allows for a maximum power delivery of 200 W +/- 20%.

2. Design

Block Diagram

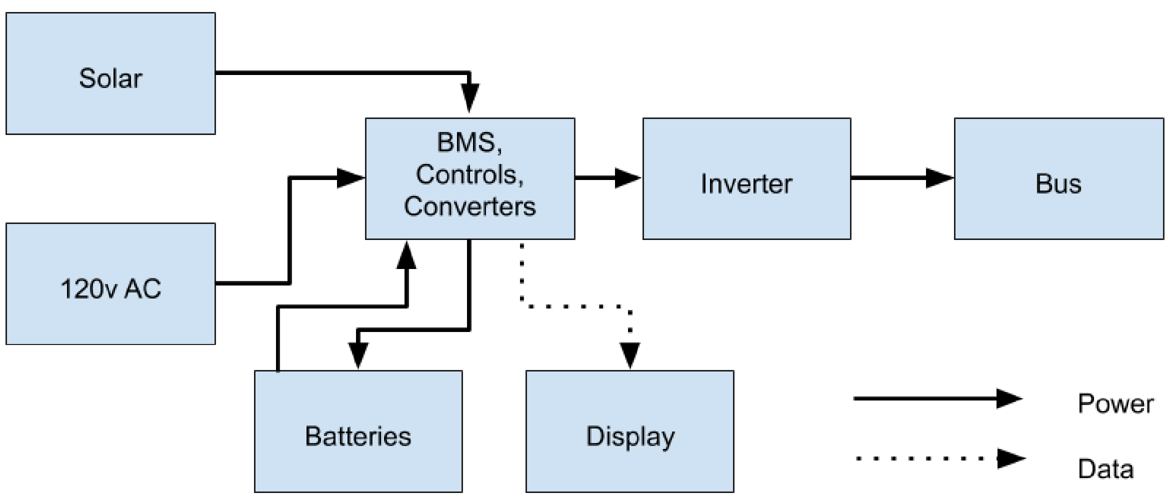

Figure 1. The high-level, power flow block diagram. Most of these components will be bought off-the-shelf. The primary exception will be the central BMS system. We will be constructing that as our PCB.

Solar - This section provides a 12v output from the solar panels that will be mounted on the bus. This will be an easy connection from the panels to the input of our BMS as both input and output voltage will be the same. If losses become a problem, we can attach a boost converter to slightly boost up the voltage to our intended range. Our proof of concept will have a small solar panel array and is expected to provide about 100W of power.

Battery - This is our battery array that will be designing and putting together. We are putting together 12 stacks of lithium ions, which will provide a voltage range from 36v to 50.4v. These batteries will be managed by the BMS. Our proof-of-concept will have a 300 W capacity. More detail in the BMS block diagram below.

Inverter - This will convert the 11-15v output from the BMS to a clean 120v AC line. This line can then be used to power the majority of the devices on the bus and keep them running.

Bus - All of the equipment that needs to be powered on the bus. Expected load of around 12 kW of 120v AC.

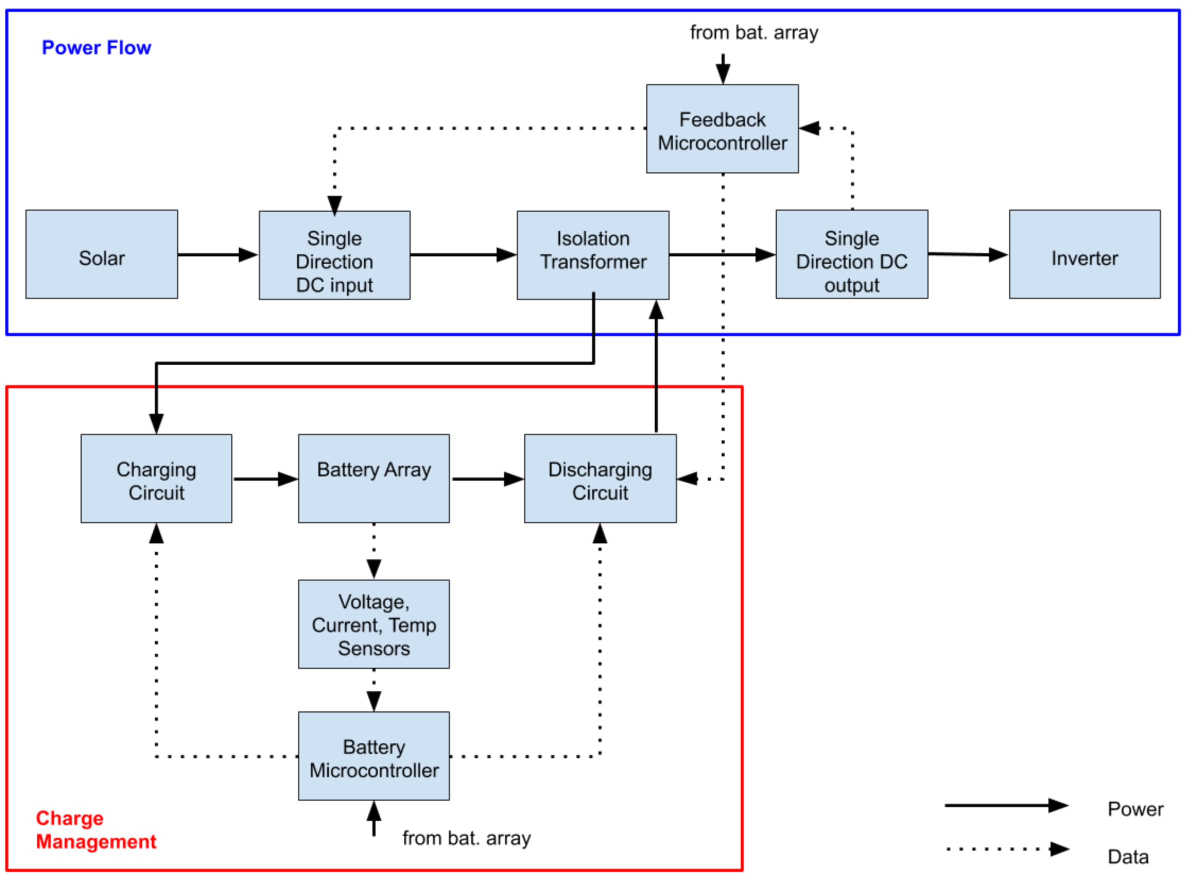

Figure 2. The BMS block diagram. We will be making most of these components on multiple PCBs. Some of these components, such as the cooling and microcontrollers, will be bought but then configured to fit our project.

Single Direction DC Input - This is an AC link converter that allows any DC input to interact with the isolation transformer. There will be multiple of these circuits due to the various input sources such as solar, AC inputs, etc. This circuit will require an AC link due to the large power delivery (<200W). It is a single direction as power will only be flowing towards the transformer from the input sources. This power slow direction will be maintained using diodes. This will take in feedback from the Feedback Microcontroller to enforce the 11-15v range regardless of variations to the input voltage.

Isolation Transformer - This transformer is in charge of isolating the various sources and loads from each other. Isolation adds a large degree of safety to overall design by limiting any short-circuit current. This when combined with fuses, adds a very large degree of fault protection. This transformer also allows for easy voltage conversions between the different blocks. This final transformer should be rated for 15kW due to the large amount of power. This smaller-scale proof-of-concept will be rated for 200 W.

Single Direction DC Output - This is an AC link converter that allows the isolation transformer to interact with the inverters. This AC link will take the alternating DC voltage from the isolation transformer and rectify it to a 11-15v DC output. This voltage output is needed to drive the inverters, which will be supplying 120v AC to the bus.

Charging and discharging circuits - This is the third and final AC link, which is bidirectional to allow power to flow both to and from the battery array. This will be operating within an input range of 36v to 50.4v and we will use feedback to provide a stable voltage to the isolation transformer. This block will adjust the voltage range by adjusting switching delays for our link. This is also responsible for providing the charging voltage to the rest of the array during the charging cycle.

Battery Array - This is the battery pack that we will be designing. We will have a 12-cell stack that will bring our operating voltage range from 36v to 50.4v. This higher voltage range allows us to draw less current from the batteries and reduce losses. It also has the side benefit of reducing the negative effects of voltage drops in the converter. To ensure that we are not overcharging, we can estimate the capacity using the voltage-capacity curve :

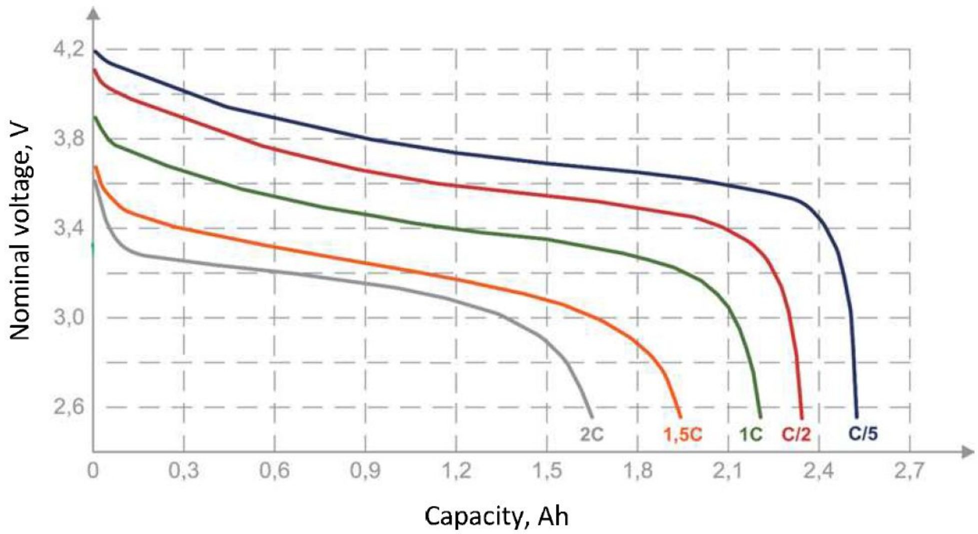

Figure 3. Typical nominal voltage - capacity curve for lithium ion batteries. [4]

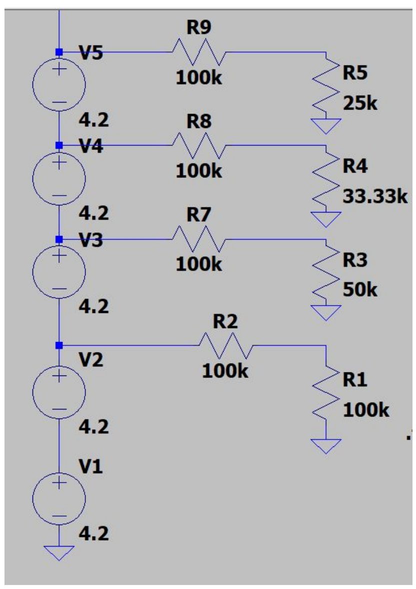

Figure 4. Measuring the voltage in the battery array. Measuring the voltage across a small resistor in series with a larger one (fixed at 100kohm for all cells) that are grounded will allow us to scale down the voltage and feed it into the microcontroller.

The formula for determining the resistance that will scale down the measured voltage into one that is < 5V is $\frac{R_b}{n-1}\ (n > 2)$, where the battery is the nth battery from ground. There are 12 batteries in total.

Feedback Microcontroller - These are responsible for adjusting the "dead time" delay of both the bidirectional link and the single directional output link. These let us drop down the voltage to required levels as the input changes. These will read in the voltage that is input to the inverter and provide the PWM signals with appropriate duty cycles to adjust the inverter's input to the appropriate range.

Voltage Sensors - This is used to directly monitor the voltage level of each cell in a stack. This ensures that the voltage of every cell is within the correct range that it needs to be at (3-4.2v per cell). If any cell falls outside that range or has a disproportionate voltage compared to the other cells in the stack, then the analog logic attached to this will send a disconnect signal to the digital logic.

Current Sensors - This is used to read the current flowing through the stack. This will allow us to monitor the current and send a shutoff signal of the current exceeding upper limits. This would then link to the rest of the digital logic. For the purposes of our test model, we will have the attached logic send the cutoff signal at 6 A per stack.

Temperature sensors - This is used to read the temperature of each stack. Each stack will have a heatsink metal link between all of the batteries which will share thermals between all of them. These thermals will then be monitored by analog logic that will send a cutoff signal to the digital logic if the temperature rises beyond the maximum threshold of 45 C or 113 F.

Battery Microcontroller - This component takes in data from the Analog and Digital circuits to build models based off of it. These models will then be sent to a display for the end user to see them. These models will include data such as power draw, remaining battery capacity, remaining run time, etc. This component should be able to scale all models based on how many stacks are plugged in along with being able to point to faulty stacks.

Requirements and Verification

Single-Direction DC Input	
Requirement	Verification
Output voltage can reach at least an average range of Vin-15% to Vin/2 +15%	1. Build H-bridge circuit with filters at the output. 2. Probe output voltage using oscilloscope. 3. Use measure/avg to ensure that voltage is within appropriate range

Isolation Transformer	
Requirement	Verification
Core is able to reach a current that is able to sustain 160 W load at minimum under test conditions	Calculate expected current that would but transformer in saturation Build test circuit that attaches electronic load to three windings of transformer Run some current x through winding 1 and draw some current y through winding 2 such that the core is not in saturation. Ensure this current allows for 160 W minimum power draw at load

Single-Direction DC Output	
Requirement	Verification
1. Voltage stays within the acceptable range for input to the inverter (11v-15v) 2. Current stays within acceptable range for inverter (>0A and <40A) including ripple	1. Use oscilloscope, probe output and ensure that voltage stays within acceptable range (excluding initial transient) Ensure voltage never exceeds (11, 15) v 2. Using a hall effect sensor on an oscilloscope, probe output current and ensure it stays within range in steady state. This will be tested with a test load.

Feedback Microcontroller	
Requirement	Verification
Given some simulated function V_{in} that lies within test range: (Test range is 36-50.4 V) 1. Output a PWM signal with duty cycle D such that $V_{out} = 2DV_{in}$ and $11v < V_{out} < 15v$ 2. Ensure that the logical low and high are appropriate for use with our gate drivers	For each V_{in} ε [36, 38, 42, 44, 46, 48, 50]: 1. Send V_{in} to microcontroller 2. Measure output V_{out} with oscilloscope 3. Ensure that $11v < V_{out} < 15v$ 4. Ensure that the "low" on the PWM lies below the logical low for our TTL chips (<0.7v) and the "high" lies above logic high (>2.5v)

Battery Microcontroller	
Requirement	Verification
1. Deliver 200W max load within +/- 20% accuracy at 36 - 50.4 V and <6 A per stack of batteries in series 2. When charging, ensure that charging at a rate < C/3 (500 mA) 3. Switching signals for charging/discharging must have appropriate delay time of 10 us +/- 20%	1. Attach 200 W electronic load to batteries Measure current at load using ammeter in series and verify current is < 6 A Measure voltage at load using voltmeter and ensure voltage is within 36 - 50.4 V range for the entire stack Ensure current*voltage is within 20% of 200W 2. Send simulated feedback loop with input current Ensure that controller can keep current less than 500 mA 3. Send simulated signals of power draw in from solar panel and out from load Ensure that when $P_{in} > P_{out}$, battery array is charging and vice versa Probe output of microcontroller with scope Ensure that as $P_{in} - P_{out}$ changes sign, a buffer of 10 us +/- 20% is achieved

Battery Array	
Requirement	Verification
1. Deliver 200W max load within +/- 20% accuracy at 36 - 50.4 V and <6 A per stack of batteries in series 2. When charging, ensure that charging at a rate < C/3 (500 mA)	1. Attach 200 W electronic load to batteries Measure current at load using hall effect and verify current is < 6 A Measure voltage at load using voltmeter and ensure voltage is within 36 - 50.4 V range for the entire stack Ensure current*voltage is within 20% of 200W 2. Attache 200 W electronic load to batteries Using hall effect sensor, measure current into batteries Ensure current is within 20% of 500 mA

Charging Circuit	
Requirement	Verification
Able to execute the two charging stages of a lithium-ion. The first stage is a constant current stage (+/- 10%) with a gradually increasing voltage.	Measure current at load using ammeter in series and verify current is < 6 A Measure voltage at load using voltmeter and ensure voltage is within 36 - 50.4 V range for the entire stack Ensure current*voltage is within 20% of 150W

Tolerance Analysis

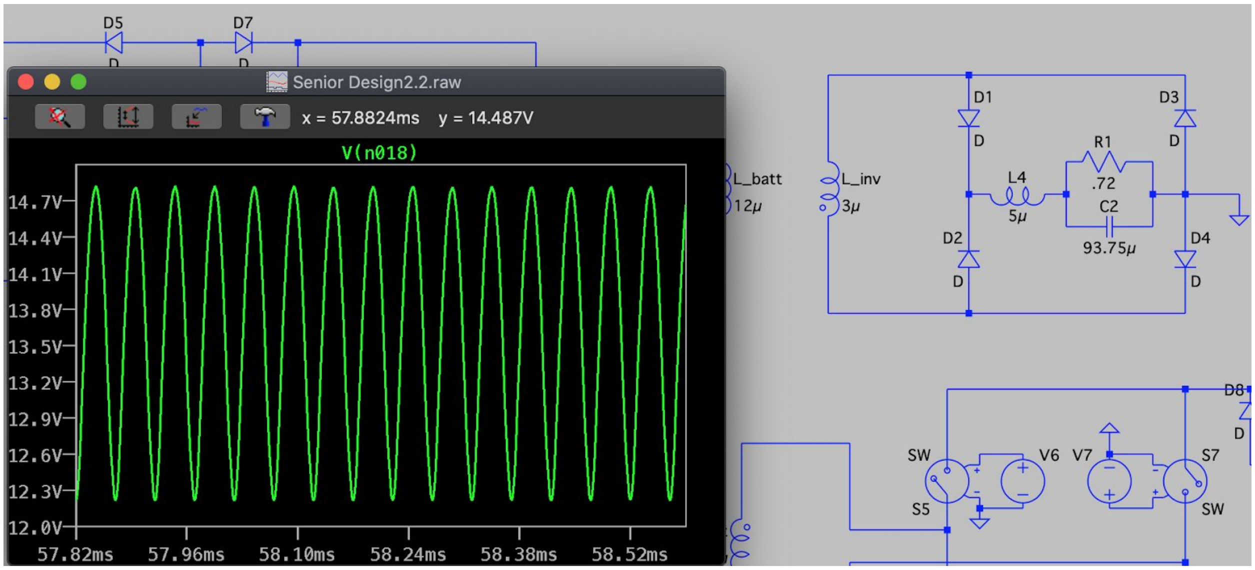

Figure 5.

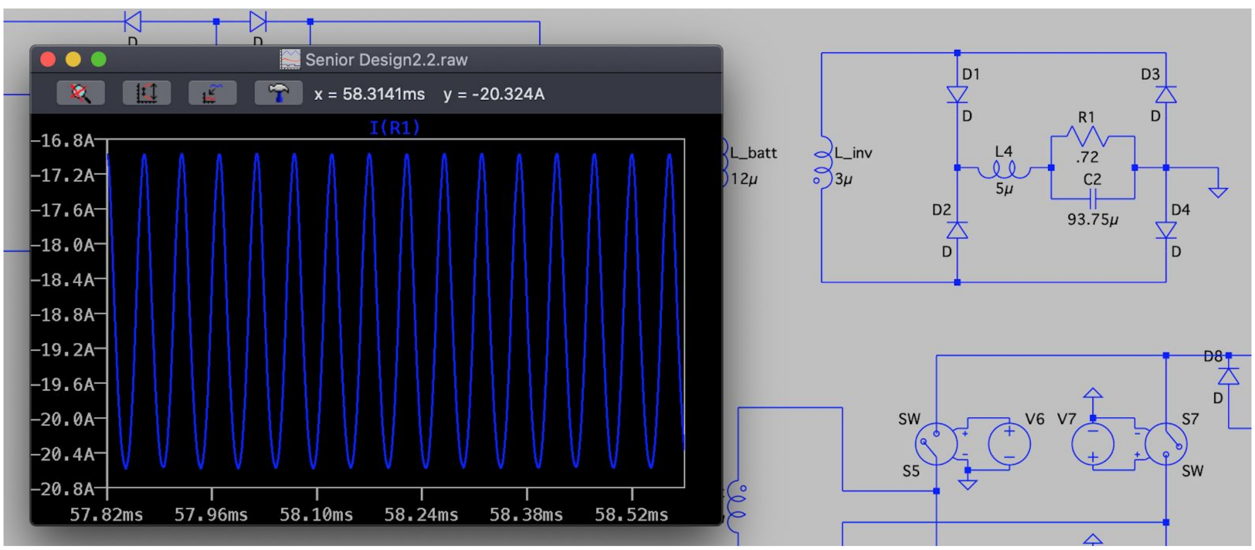

Figure 6.

Figure 5 and 6 are simulations of the output into the inverter. The inverter that we plan on using is rated for a voltage range of 11-15v and a current limit of 40A. The established value for our filters leave us comfortably in that range. This should allow our inverter to supply a reliable sine wave to any plugged in devices. This circuit is a basic full-bridge rectifier that takes the AC pulses from the transformer and converts them into DC pulses. The inductor and capacitor filters then smooth out the pulses to an acceptable range for the inverter.

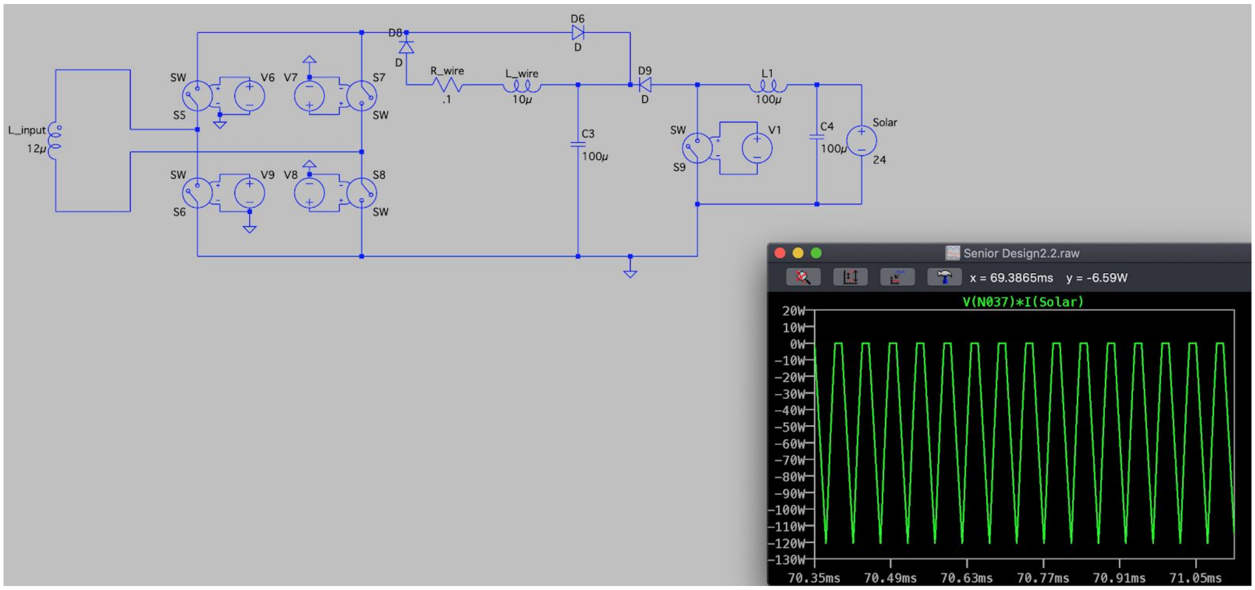

Figure 7.

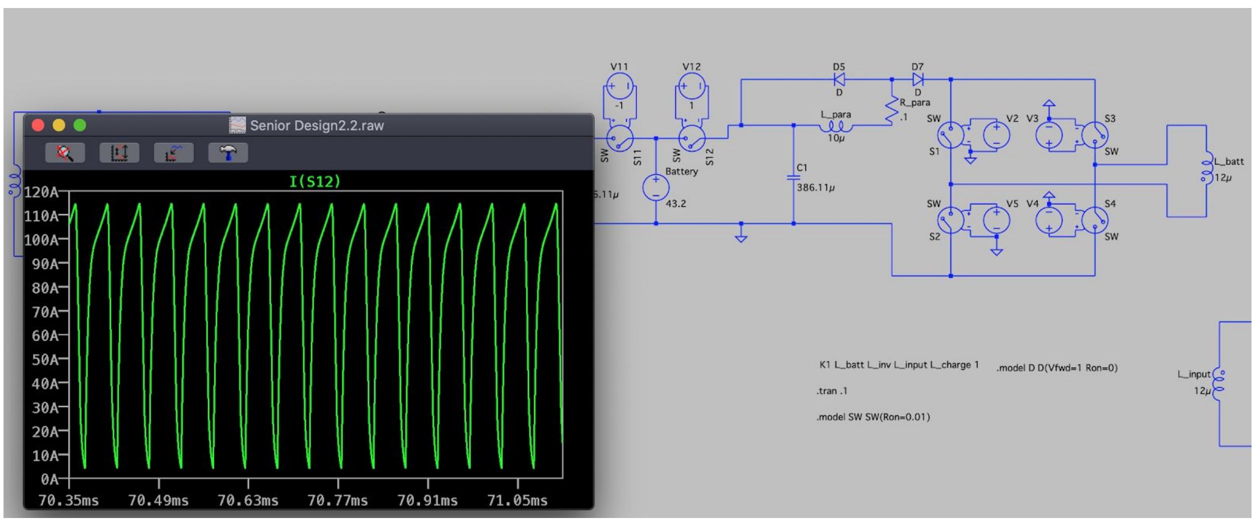

Figure 8.

Figure 7 and 8 are the battery discharging and solar circuit. These circuits allow for power to flow into the transformer and thus into any attached loads. During battery discharge mode, the load will only be the inverter. The inverter will then power whatever is plugged into it. During battery charging mode, the load will be both the inverter and the battery itself. The two figures are fairly similar to each other, but there are some key differences between the two. The main component for these two circuits is a full-bridge converter that takes some DC voltage and creates AC pulses. These pulses can then be fed into a transformer. We are currently planning on adjusting our duty cycle based off of the voltage of the battery pack to ensure a steady voltage at the inverter. The solar circuit will follow this duty cycle to prevent extra interference from causing voltage spikes throughout our circuit. In particular, it created fairly large voltage spikes in the output to the inverter. Therefore, to adjust the power heading into the transformer, there is an attached boost converter. This boost converter allows us to keep the same duty cycle into the transformer while also adjusting the power flowing from the solar panel.

The circuit in figure 7 is still somewhat up for debate however. We currently also have a design for a different converter topology that is showing good promise. A forward converter would allow the solar power into the transformer while using less switches, and possessing an easier switching algorithm.

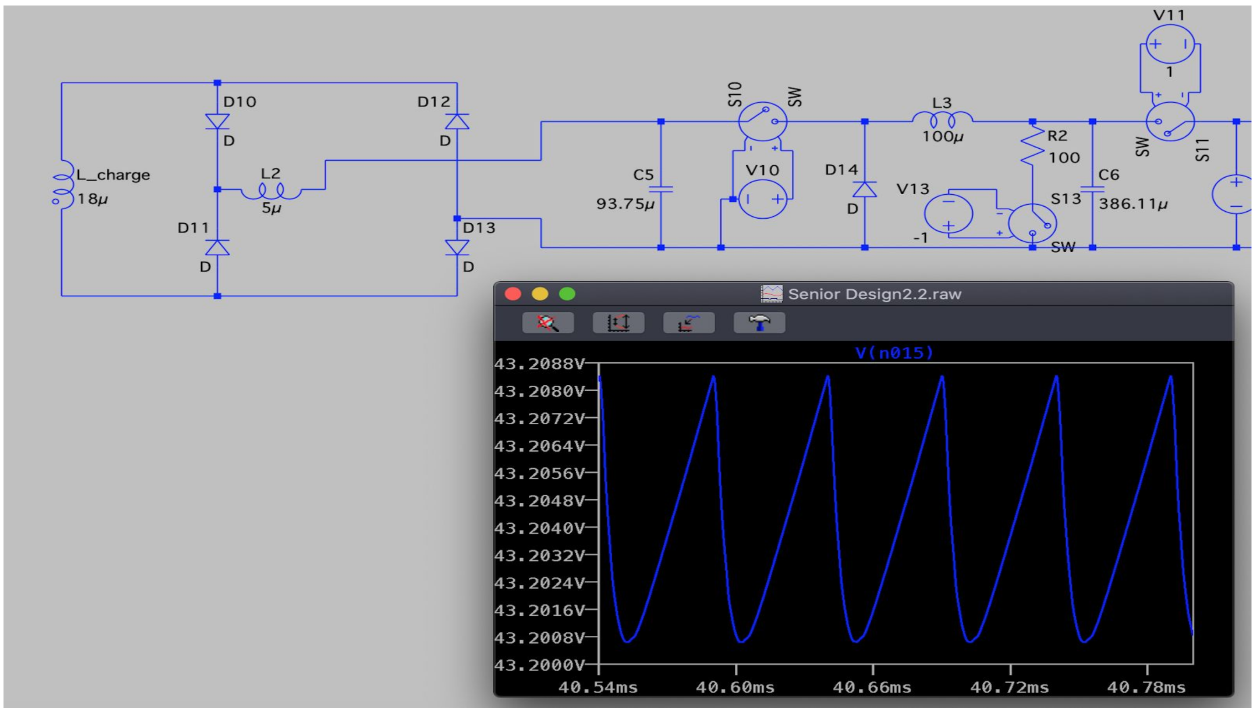

Figure 9.

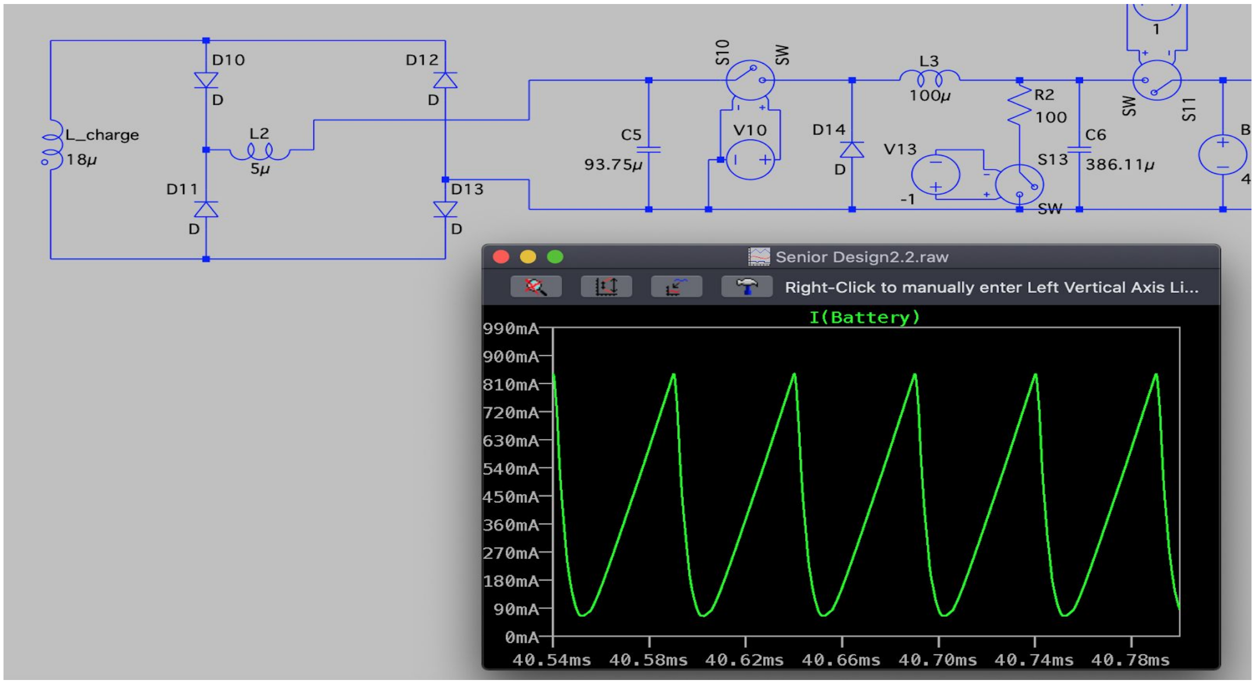

Figure 10.

This is the charging circuit that will manage the batteries. This initially begins as the same circuit as the output to the inverter. It has identical filters and topology as it is a full-bridge rectifier. The difference is that this converter has an attached buck converter. The buck converter allows for fine voltage control, which will allow for the two seperate charging modes. During mode 1, current is kept constant while voltage is slowly increased. We can change the voltage by slowly changing the duty cycle of the converter as the voltage of the battery increases. During mode 2, the voltage must be kept at a very controlled level before it is shut off. This converter topology allows for this fine control that can and a slight modification allows the converter to be safely shut off when the system changes back to discharge mode.

Schedule

Week	Antonio	Anabel	Eros
3/2/2020	Continue working on Schematic	Calculate timing for switching	Perform simulations
3/9/2020	Finalize schematic and parts	Finalize Sensor Parts	Purchase Parts and Microcontrollers
3/16/2020	Finalize and Order PCB	Start Creating Switching controller	Initiate programming of sensors
3/23/2020	Work on PCB	Work on PCB	Initiate switch program/ Work on PCB
3/30/2020	Work on PCB	Work on PCB/Help With Switch Program	Continue switch programming/ Work on PCB
4/6/2020	Make Transformer/Start Unit Testing	Make Transformer/Start Unit Testing	Maker Transformer/Start Unit Testing
4/13/2020	Combine All Units	Combine All Units	Debug any Coding problems
4/20/2020	Conduct Testing	Conduct Testing	Conduct Testing
4/27/2020	Prepare Final Presentation	Prepare Final Report	Prepare Final Report

Parts List

Description	Manufacturer	Part No.	Quantity	Cost
Temperature sensor	Digikey	MCP9700A-E/TO-ND	1	$0.31
Lithium Ion batteries 25R 18650 2500mAh 20A	Samsung	INR18650-25R	12	$39.00
300Watt Pure Sine Wave Power Inverter DC 12V to AC 110V with 4.2A	BESTEK	8523712696	1	$45.99
Hall Effect Current Sensor	Digikey	620-1541-5-ND	1	$7.18
0.1 uF capacitor	ECE Supply Store	1C20Z5U104M050B	1	$0.43
0.01 nF capacitor	ECE Supply Store	1C20Z5U103M050B	1	$0.23
1/4WATT 5% RESISTOR KIT	ECE Supply Store	COM-10969	1	$9.29
			Total:	**$102.20**

Labor Costs

Member	Hourly Rate	Hours	Total
Antonio	$50	300	$15,000
Anabel	$50	300	$15,000
Eros	$50	300	$15,000
		Total:	**$45,000**

Total Estimated Cost: $45,102.20

3. Ethics and Safety

Lithium ion batteries have a large energy density and their mode of failure, when physically impacted or operated improperly, can be fire or an explosion [5]. Because the bus will need large amounts of energy to be stored, we must ensure that the power is always safely managed. Although we are only building a small-scale model, while designing our project we need to keep in mind the effects of scaling it up to a large scale capable of storing up to a few dozen kWh. To protect the safety of those who will use and operate the bus in the future, we have recommended to those who proposed the idea to take our design to a professional engineering firm to build the full power-management system. We will also actively seek feedback for our work as the project is progressing.

As stated in the IEEE Code of Ethics [6], we must hold the health and safety of the general public in the highest regard. Multiple layers of monitoring and redundant emergency shut-off mechanisms help us achieve safe use of the system. We must ensure that proper education is given to those who will be operating the bus to understand the dangers of lithium ion batteries to deter reckless behavior or operation of the system, and, as ethical engineers, give our best estimates of the dangers that could arise given the data we have been presented.

Since this bus will be driven on highways with the lithium-ion batteries, a hazardous material, we must comply with the Electronic Code of Federal Regulations § 173.185 Lithium cells and batteries [7]. In order to transport the amount of power ultimately needed, each battery cell and pack will need to be properly insulated, away from metal or conductive surfaces, and secured with an inner packaging. We must ensure that the surrounding material has a resistance of at least 500 ohms/V. Then, each pack must be completely encased in an outer packaging that is drop-proof (up to 1.2 m), impact-resistant, and protects the batteries from debris, while ensuring vibrations due to movements of the bus do not cause the batteries to impact each other. The BMS must ensure the system does not inadvertently turn on during transport. Each outer packaging should be secured to the floor of the bus. The outer packing must have markings declaring its contents, and have proper ventilation for thermal regulation.

Before using our system for the first time we must perform some tests and record reference data for our system. As stated in [5], we must record the internal resistance across each cell and ensure no more than a 15% variation between cells. The open-circuit voltage across cells should have no more than a 2% variation between cells at all times. Maintenance, including cleaning any chemical leaks, verifying secure connections of batteries and checking for deformities, should be performed regularly. The system should also be checked for energy leakage. Our battery management system will record and transmit data about the state of charge and state of health of each group of cells, voltage, and current. The information will be presented in a user-friendly manner, as suggested in the above Guide.

References

[1] *The Hip Hop Xpress*. [Online]. Available: https://publish.illinois.edu/hiphopxpress/. [Accessed: 13-Feb-2020].

[2] P. T. Krein, *Elements of power electronics*. New York: Oxford University Press, 2016.

[3] D. Marcos *et al*., "A Safety Concept for an Automotive Lithium-based Battery Management System," *2019 Electric Vehicles International Conference (EV)*, Bucharest, Romania, 2019, pp. 1-6.

[4] I. Starostin, S. Khalyutin, A. Davidov, A. Lyovin and A. Trubachev, "The Development of a Mathematical Model of Lithium-Ion Battery Discharge Characteristics," *2019 International Conference on Electrotechnical Complexes and Systems (ICOECS)*, Ufa, Russia, 2019, pp. 1-4.

[5] IEEE Guide for Design, Operation, and Maintenance of Battery Energy Storage Systems, both Stationary and Mobile, and Applications Integrated with Electric Power Systems," in *IEEE Std 2030.2.1-2019* , vol., no., pp.1-45, 13 Dec. 2019

[6] “IEEE Code of Ethics,” *IEEE*. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed: 14-Feb-2020].

[7] “§173.185 Lithium cells and batteries.,” *Electronic Code of Federal Regulations (eCFR)*. [Online]. Available: https://www.ecfr.gov/cgi-bin/text-idx?SID=c9068f6400017f54b47e59b9d4e5d486&mc=true&node=se49.2.173_1185&rgn=div8. [Accessed: 13-Feb-2020].