SOLAR POWERED RECHARGEABLE BATTERY PACK WITH CONTROLLABLE VOLTAGE OUTPUT

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Abstract

The goal of this project is to develop a battery pack that could be self-recharged by solar cells and outputs controllable voltages at different levels. The solar cells could be mounted on the system in a portable box. The output of the battery is controlled and monitored by microcontroller and is adjustable and visible for users. Users could select the preferred voltage level on the user interface. This project aims to provide user an oriented battery pack with portability, flexibility, and endurable capacity for the increasing use of battery today. By using batteries with different capacities and small configurations on the design, this system could be applied to various situations like electrical vehicles, cell phones, or smart home batteries.

Contents

1. Introduction

1.1 Objective

We are now at the crossroad of our industrial civilization. The traditional power sources like oil or other fossil fuels can no longer fulfill our expanding demand for energy. Therefore, more and more people are using renewable resources like solar, wind, or tide. There are two usually ways to deal with this kind of energy: we use it or we store it. Most of the power generated from large solar farms or wind farms would directly merge into the power grid while using the thermal generator sets to perform the frequency regulations. This method is deficient, since the motor start-up and spin-down would cost large amount of extra energy, which is both economically and physically inefficient. So, considering of this situation, the alternative would be storing the power generated from renewable resources to batteries or pumped storages. Unlike the diversifying input resources, the output of electricity is stagnant comparing to the explosively increasing use of all kinds of electrical devices. Cell phones, electric vehicles, and smart home devices are surrounding modern people. However, the various charging voltage levels really confuses most of the people, requiring additional converters or inverters, which is inconvenient for people with no general knowledge about electricity.

Modern society and industry thrive on top of electricity. Electrical energy could be generated from and converted to various source of energy. It has the most sophisticated system to transmit the energy safely and efficiently. However, even though the uses of batteries are increasing and diversifying, the technology of battery is stagnant. People today would really suffer from such problems. Those who want to set a solar panel for the house would really confused on which batteries to be used. Since most of the batteries output standard dc voltages, it is hard for people with no technical backgrounds to adapt the batteries to ac voltages. So, this system is developed in order to make better use of battery that could self-recharge and have the ability to output different voltage levels to accord with different demand. The system could apply to various situation. The system with a larger battery could be applied to electric vehicles. With self-recharging, vehicles could have greater endurance, and with the ability of outputting different voltage levels, the single system could be used as power source for driving, electrical devices on the vehicles, or mechanical operations.

1.2 System Overview

To achieve our goal of this project, we require three modules: an input module, an output module, and a control module. Figure 1 shows a block diagram for this project and Figure 2 shows the actual physical design of this device. The input module provides power supply for the system from some external sources. As you can see, the input module has two different input sources: an AC power supply from the wall outlet and a DC source directly from the solar panel. It contains an AC battery charger and a solar charging system. The output module contains a DC/DC converter in series with an inverter that can output either AC or DC voltage. The inverter is connected with a transformer to step up the output AC voltage. The control module contains a microcontroller power supply module that can draw power from the battery and supply energy to the microcontroller, a battery measurement system that can monitor the charging and discharging process of the battery, a microcontroller that controls the output DC/DC converter to output the proper voltage level, and a user interface that can collect the user input parameters and display the system status. The battery pack contains several lead-acid batteries connected in parallel which stores the electrical energy from the external sources and supply energy to the entire system.

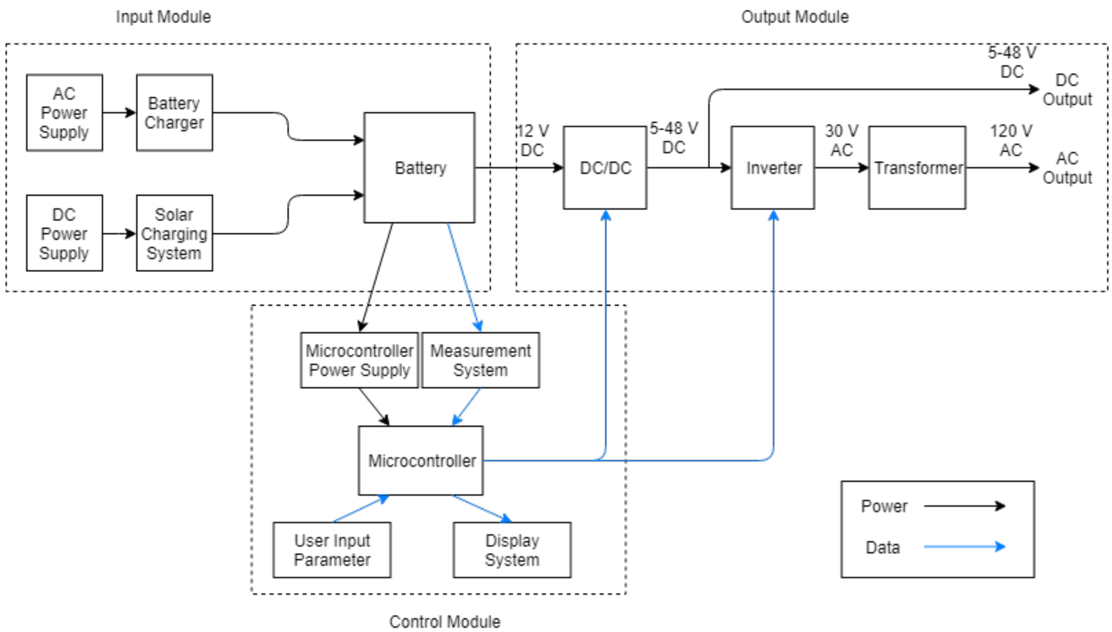

Figure 1: Block Diagram

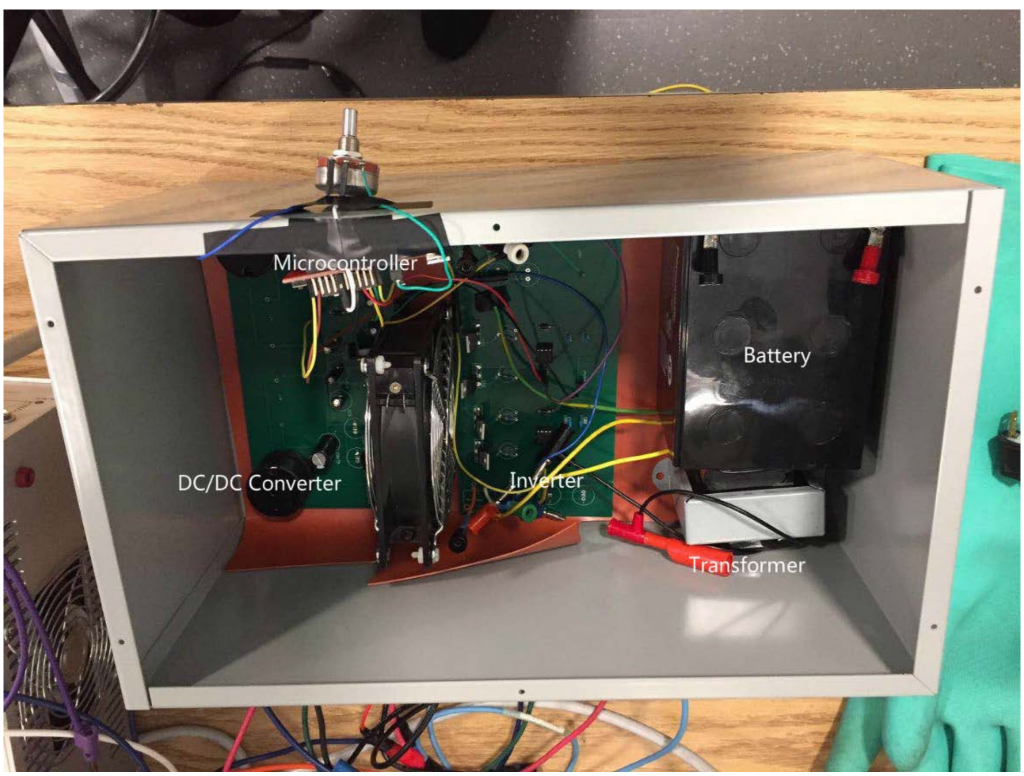

Figure 2: Physical Design

1.3 High-Level Requirements

- The system must be able to be recharged from both the mounted solar panel and wall plug.
- The system must be able to discharge 5V - 48V DC power, and 120V AC power based on user selection.
- The system need to display the voltage, current, and power on the LED screen while charging or discharging.

2 Design

2.1 Input Module

2.1.1 Battery

The battery pack is responsible for storing the electrical energy from the external sources and supplying energy to the entire system. We used a Panasonic 12 V 12 Ah rechargeable Lead-acid battery as our power source. The battery voltage will be varied from 11.4 V (fully depleted) to 12.7 V (fully charged). The capacity of this battery could be varied based on the discharging rate.

2.1.2 AC Battery Charger

For safety reason, we did not build our own battery charger because the lead-acid battery requires an extremely precise charging process. Over-charging or incorrectly charge a lead acid battery can produce hydrogen sulfide which can become explosive at a concentration of 4 percent. Instead of building an ineffective, unsafe battery charger, we used an off-the-peg battery charger to minimize the risk of incorrectly handling the battery. Another advantage of using this battery charger is that it is equipped with built-in reverse polarity, short circuit protection and over-temperature protection. Those safety measures give user piece of mind about their batteries and this charger system.

2.1.3 Solar Battery Charger

We decided to not include the solar panel and solar charging system in our project because we wanted to focus on the output end of our system. In our original design thoughts, the input power module is the charging method we want to use to increase our device's flexibility. We thought it is more important to complete the output functionality of our project because the goal of this project is to provide users an oriented battery pack with portability, flexibility, and endurable capacity.

2.2 Output Module

2.2.1 DC/DC Converter

The DC/DC power converter could output a constant DC voltage based on user's requirements. It is a buck-boost converter that can buck down or boost up the input voltage to the desired output voltage level. There are 5 main types of dc-dc converters. Buck converters can only reduce voltage, boost converters can only increase voltage, and buck-boost, Cúk, and SEPIC converters can increase or decrease the voltage. Buck-boost converters can be cheaper because they only require a single inductor and a capacitor. However, these converters suffer from a high amount of input current ripple. This ripple can create harmonics; in many applications these harmonics necessitate using a large capacitor or an LC filter. This often makes the buck-boost expensive or inefficient. Another issue that can complicate the usage of buck-boost converters is the fact that they invert the voltage. Cúk converters solve both of these problems by using an extra capacitor and inductor. However, both Cúk and buck-boost converter operation cause large amounts of electrical stress on the components, this can result in device failure or overheating. SEPIC converters solve both of these problems. The SEPIC converter is a buck-boost converter with a coupled inductor which can split into two isolated inductors. It provides a positive regulated output voltage from an input voltage that varies from above to below the output voltage. Since our converter's output is also inverter's input, we must consider about the common ground issue. Therefore, we chose the SEPIC converter as our output DC/DC converter. For our project, the DC/DC converter is responsible for drawing power from the battery at 12V and converting this voltage into a range of output voltage (5 - 48 V). The microcontroller could generate the PWM signal that is required for the converter to control the output voltage magnitude. Figure 3 shows the SEPIC operating in continuous conduction mode (CCM).

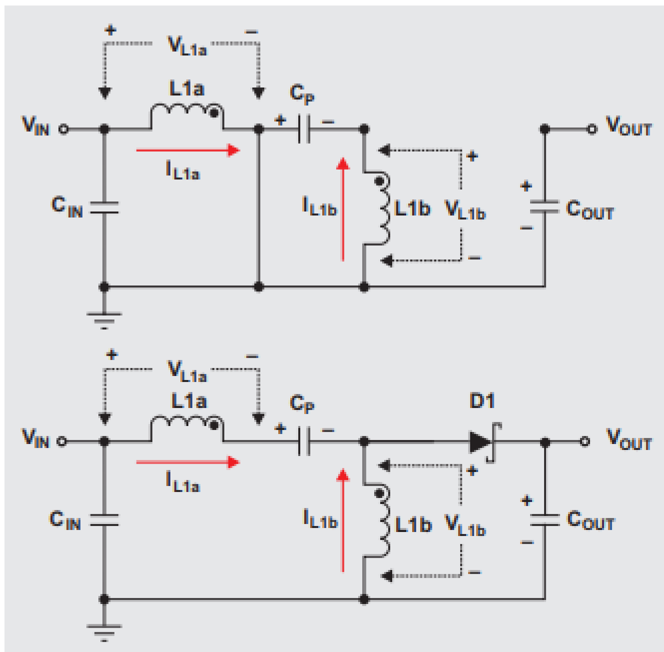

Figure 3: SEPIC during CCM operation when Q1 is on (top) and off (bottom)

When Q1 is off, the voltage across L1b must be V_{OUT}. Since C_{IN} is charged to V_{IN}, the voltage across Q1 when Q1 is off is $V_{IN} + V_{OUT}$, so the voltage across L1a is V_{OUT}. When Q1 is on, capacitor C_P, charged to VIN, is connected in parallel with L1b, so the voltage across L1b is $-V_{IN}$. The duty cycle, D, for a SEPIC converter operating in CCM is given by

$$D = \frac{V_{OUT}}{V_{IN} + V_{OUT}} \tag{1}$$

This can be rewritten as

$$\frac{V_{OUT}}{V_{IN}} = \frac{D}{1 - D} \tag{2}$$

Where $D_{(max)}$ occurs at $V_{OUT(max)}$, and $D_{(min)}$ occurs at $V_{OUT(min)}$. For our project, the maximum output voltage is 48 V and the minimum output voltage is 5 V, which gives

$$D_{\max} = \frac{48}{48+12} = 0.8 \tag{3}$$

$$D_{\min} = \frac{5}{5+12} = 0.29 \tag{4}$$

With 30% current ripple, the passive components sizes can be calculated as

$$I_{in(\max)} = I_{out(\max)} \frac{D}{1-D} = 1 \times \frac{0.8}{1-0.8} = 4\text{A} \tag{5}$$

$$\Delta I_L = k \times I_{in(\max)} = 0.3 \times 4 = 1.2\text{A} \tag{6}$$

$$L_a = L_b = \frac{D_{\max} \cdot V_{in}}{\Delta I_L \cdot f_{sw}} = 80\mu\text{H} \tag{7}$$

$$C_{out} = \frac{I_{out} \cdot D_{\max}}{\Delta V_{C_{out}} \cdot f_{sw}} = 16\mu\text{F} \tag{8}$$

$$C_{in} = \frac{\Delta I_L}{8 \cdot \Delta V_{C_{in}} \cdot f_{sw}} = 1.25\mu\text{F} \tag{9}$$

$$C = \frac{D_{\max} \cdot I_{out}}{\Delta V_C \cdot f_{sw}} = 16\mu\text{F} \tag{10}$$

A simulation model is constructed based on these components sizes and shown in Figure 4.

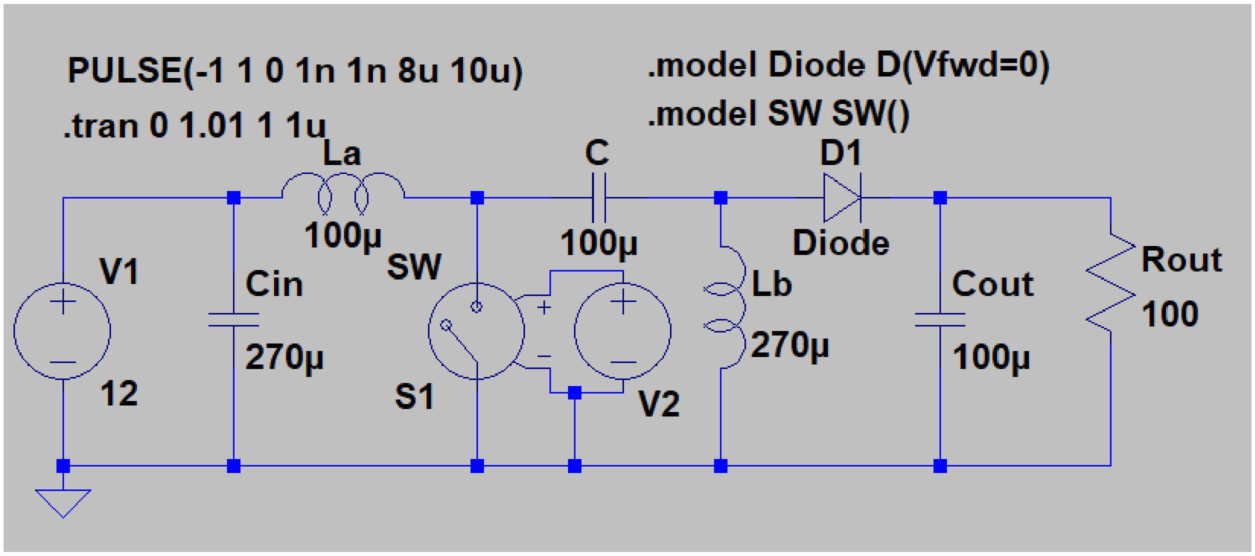

Figure 4: DC/DC Converter Simulation Layout

As you may have noticed, we chose relatively larger value for capacitors and inductors to reduce the voltage ripple. The simulation result is shown in Figure 5. The input voltage is 12 V and the output voltage is 39.99 V with 80% duty ratio.

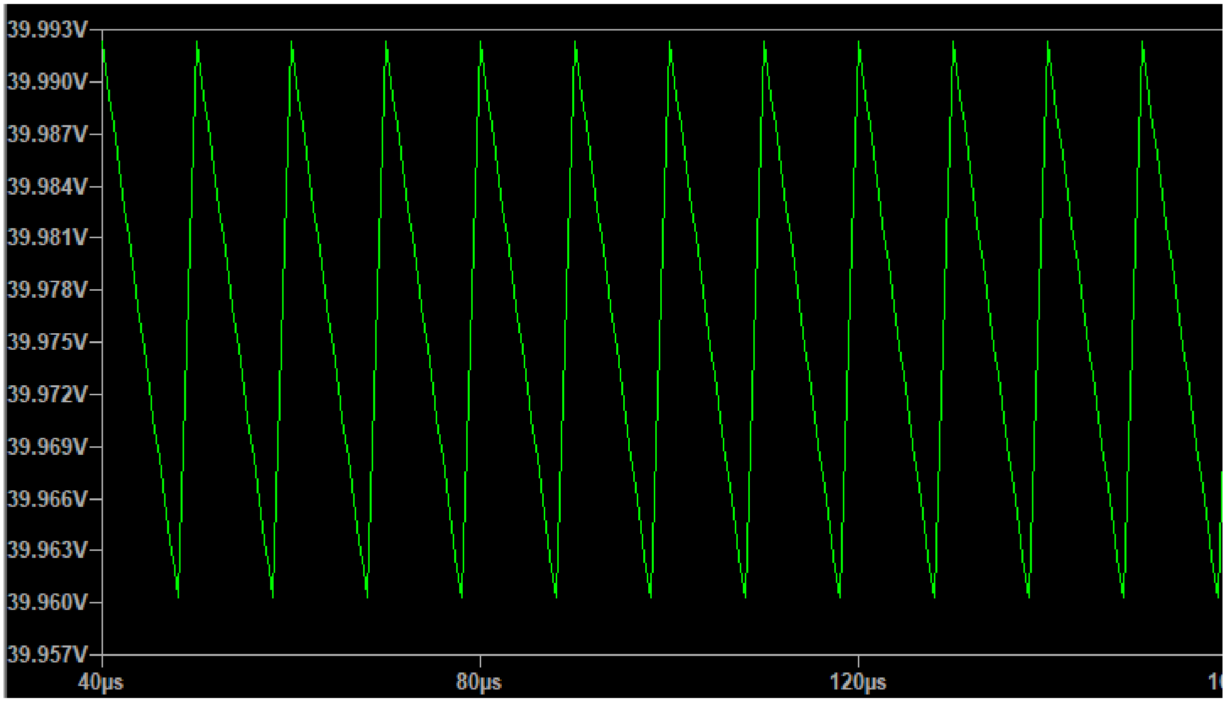

Figure 5: DC/DC Converter Simulation Result

Figure 6 shows the schematic of our converter. The gate driver we used is IRS2186. It is a High-side/Low-side gate driver with two independent high-side and low-side referenced output channels which could also be used as our inverter's gate driver.

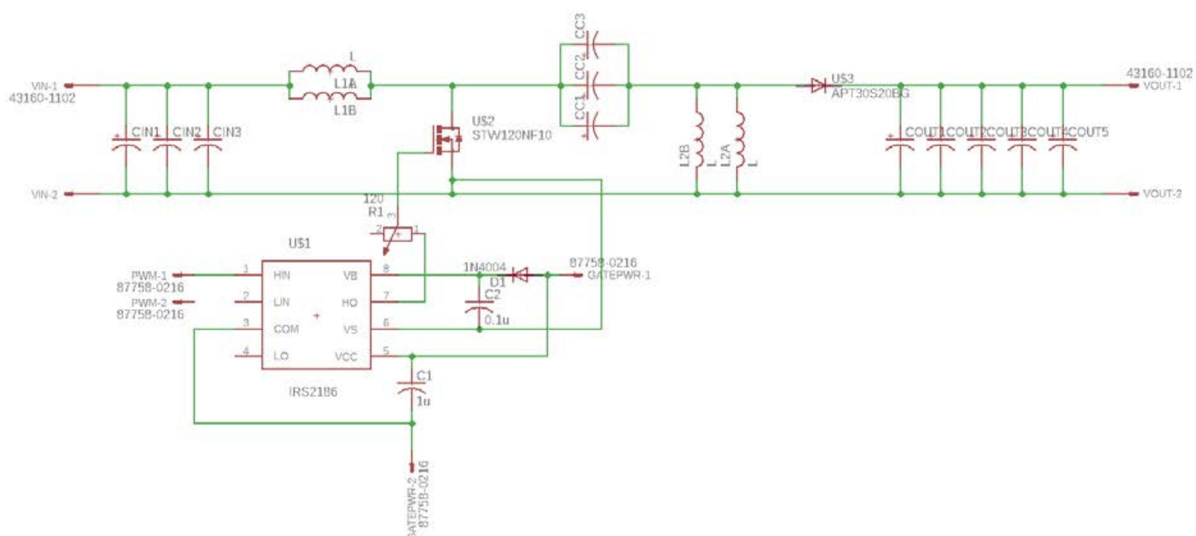

Figure 6: DC/DC Converter Schematic

Throughout our project design, the biggest challenge we have ever faced is the efficiency improvement of the converter. When we first soldered everything on the PCB we found out that our converter's efficiency was too low to reach the high output voltage condition. In order to increase the efficiency, we first tried to add more capacitors and inductors connected in parallel to reduce the total ESR. However, this only gave us about 5% efficiency improvement. Then we realized that our gate driver was not driving our MOSFETs correctly. We figured out that our MOSFETs need low side gate driving while we used the high side output channel of our gate driver during the PCB design. We had to replace a new MOSFET with the capability of both high-side and low-side gate driving. This replacement gave us 10% efficiency improvement and we finally reached up to 80% efficiency of our converter which satisfies our requirement.

Another problem we have encountered is the efficiency decrease of the MOSFET. Based on Figure 7 and Figure 8, we noticed that the drain-to-source resistance increases as the temperature increases and the maximum drain current decreases as the temperature increases. These effects could significantly reduce the MOSFET's efficiency which could cause the output voltage increases as the temperature increases. Therefore, our converter's output voltage could not be stabilized due to the efficiency change of the MOSFET.

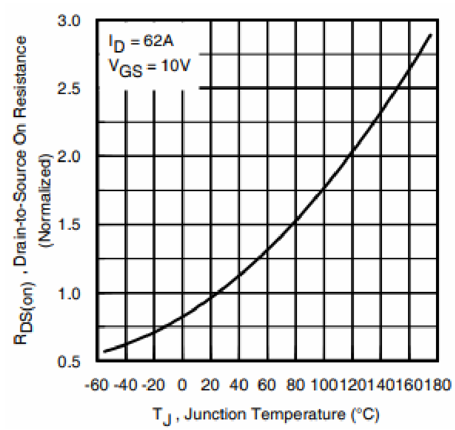

Figure 7: Normalized On-Resistance vs. Temperature

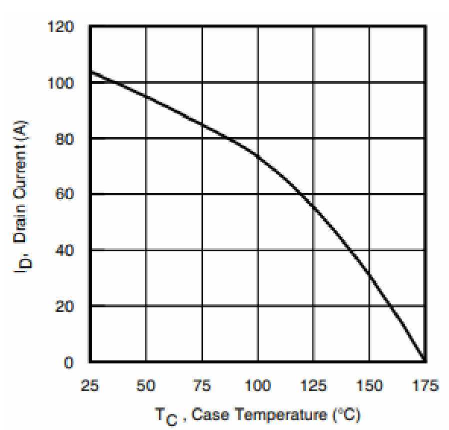

Figure 8: Maximum Drain Current vs. Case Temperature

2.2.2 Inverter

The inverter could convert the input DC voltage into a sinusoidal AC voltage. For our inverter design, we used a full bridge inverter with four MOSFET switches. We use full bridge inverter instead of half bridge inverter because the half bridge inverter has the disadvantage of being unable to eliminate the harmonic. According to IEEE THD Limitations, the total harmonic distortion should be less than 5%. For this project, we decided to eliminate the 3rd harmonic which will significantly reduce the THD. In order to eliminate the 3rd harmonic, SW1 and SW4 must have a phase shift of 30 degrees which gives zero 3rd harmonic

$$V_3 = \frac{4V_{DC}}{3\pi}\cos(3\cdot\sigma) = \frac{4V_{DC}}{3\pi}\cos(3\cdot 30) = 0 \tag{11}$$

The input of the inverter comes from the output of the converter. And the output of the inverter will go through a transformer to step up to the higher AC voltage level. The gate drives of these MOSFETS are controlled by a periodic PWM function from the microcontroller. Furthermore, an output RLC filter was applied to further reduce the THD. Figure 9 and 10 show the simulation schematic and result of the output inverter. The input voltage is 42 V which gives a 30 V_{RMS} AC output voltage.

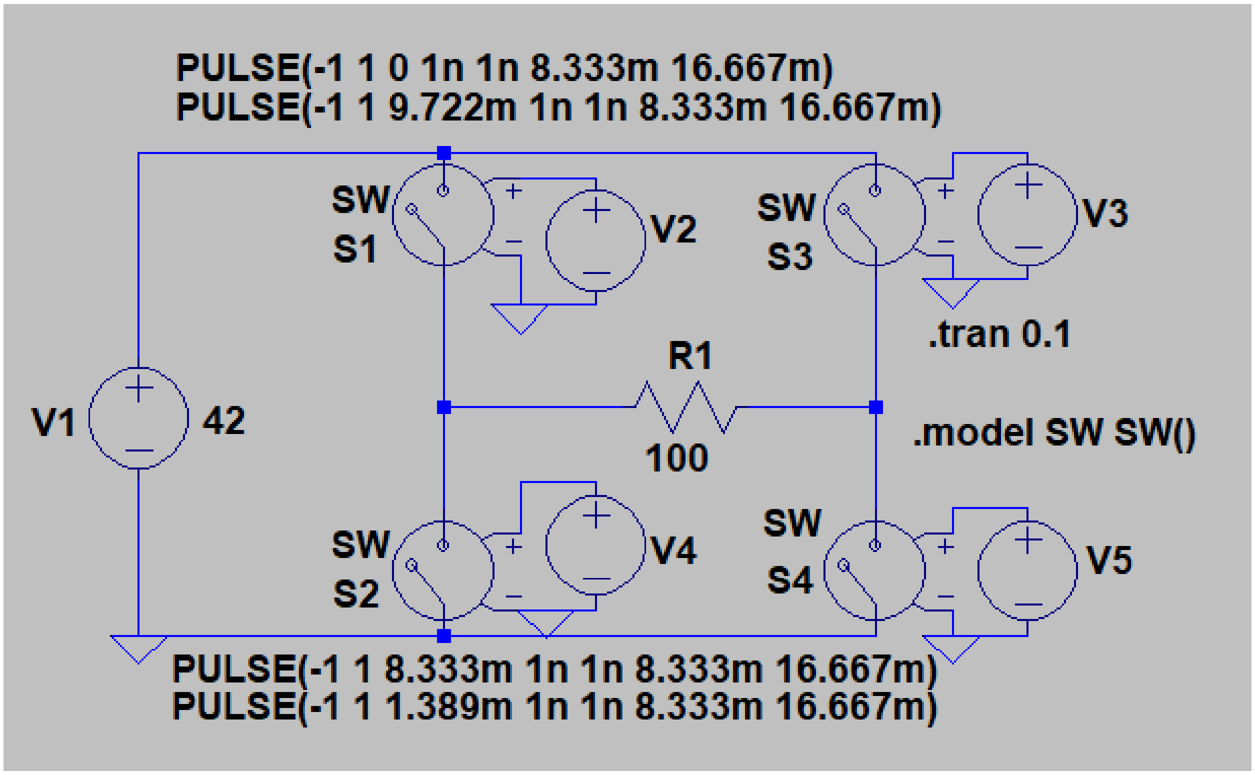

Figure 9: Inverter Simulation Layout

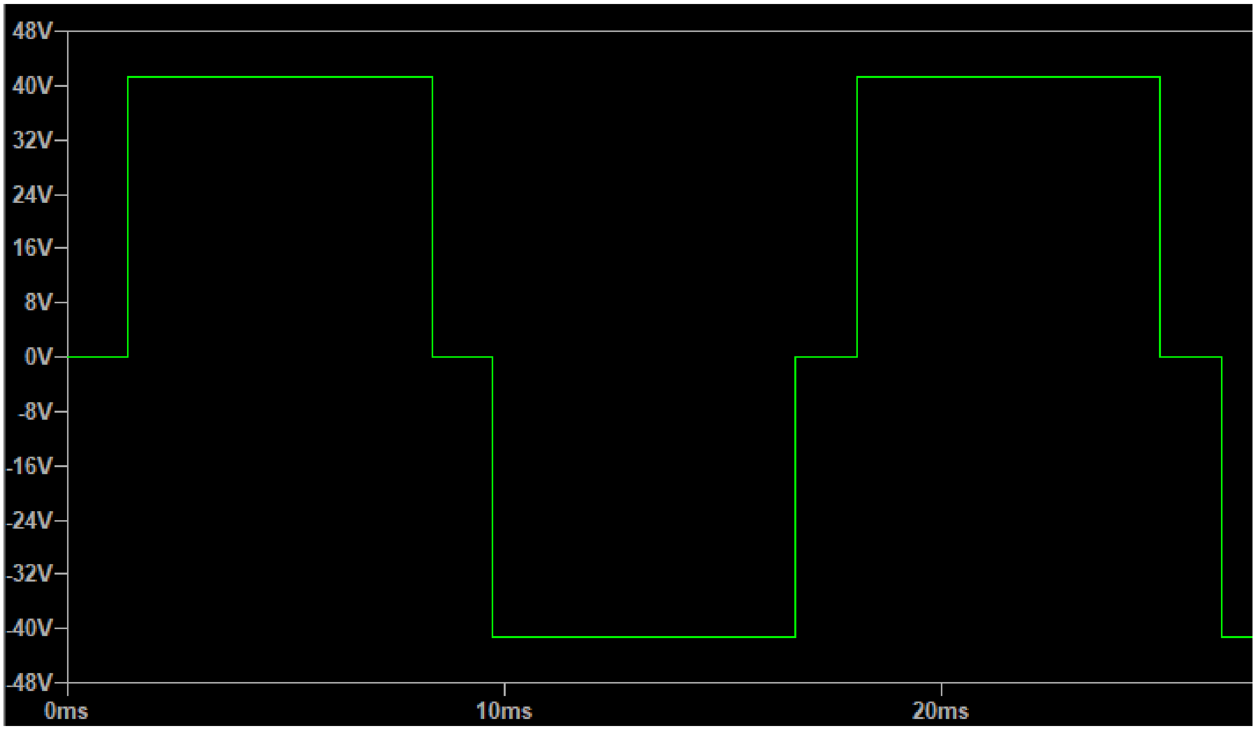

Figure 10: Inverter Simulation Result

Figure 11 and 12 show the schematic and PCB layout of our inverter design. The gate driver we used for inverter is the same as the one we used before for the converter. It has two independent high-side and low-side output channels which could control two switches simultaneously.

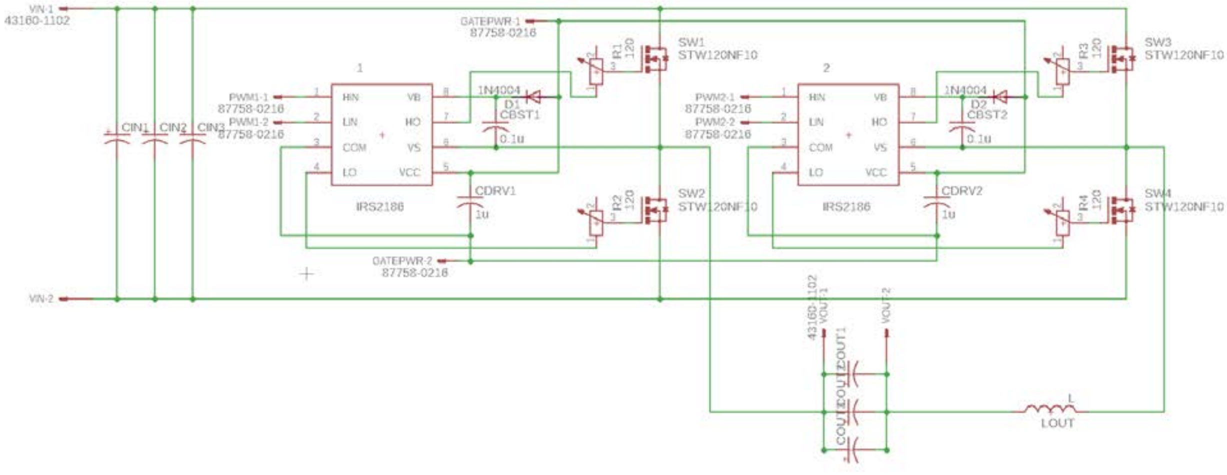

Figure 11: Inverter Schematic

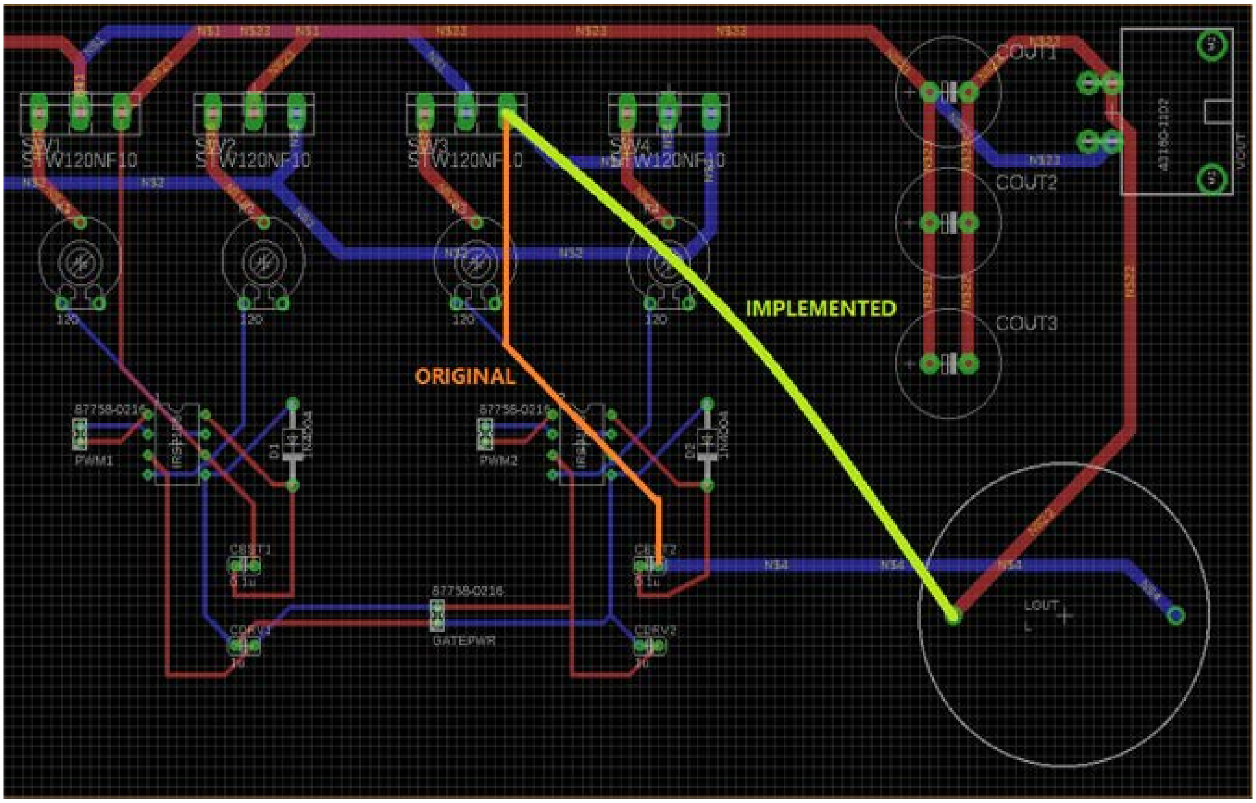

Figure 12: Inverter PCB Layout

There is flaw of our inverter's PCB design. The original small logical trace highlighted in orange is responsible for carrying the main power of our inverter circuit. However, it is too thin to carry this large amount of power and we actually burned out several gate driver chips and even one of our PCBs during the test. We fixed this problem by soldering a wire directly from the negative end of the inverter's output to the positive end of the inverter's output. The implemented line highlighted in yellow takes the main power of the inverter circuit now.

2.2.3 Transformer

The transformer is connected with the output of the inverter to step up the inverter's output voltage. Since our inverter's output is 30 V_{rms}, we need a 1:4 transformer to step up the output voltage to the desired maximum value of 120 V_{rms}. We used a transformer with the primary voltage rated at 115 V and the secondary voltage rated at 30 V. This gives us a transformer with the turn ratio of 1:3.5. We could adjust the duty ratio of the converter to finally get a 120 V_{rms} AC output.

2.3 Control Module

2.3.1 Microcontroller

The microcontroller collects all the data from the battery measurement system and compare these data with user's input parameters to determine the operation mode of the output power converters. In addition, it can also monitor the charging process to prevent batteries from overcharging. We used the Texas Instruments C2000 Piccolo and Arduino because of their optimized performance in different operations. The C2000 has advantage in closed loop feedback operations. It also has multiple enhanced PWM outputs, which can be used as the gate driver for the switches. The Arduino has advantage in measuring the voltage and current using some analog sensor and displaying these parameters through an LCD screen.

2.3.2 User Interface

This device includes a rotary potentiometer connected with the microcontroller which allows users to control the output power level. The user input will be read by the microcontroller as an analog voltage. User can adjust the output voltage level based on specific requirements.

2.3.3 Measurement System

This system contains two ACS711 hall effect linear current sensors that can monitor the output current levels during the discharging process. This device consists of a linear Hall sensor circuit with a copper conduction path located near the surface of the die. Applied current flowing through this copper conduction path generates a magnetic field which is sensed by the integrated Hall IC and converted into a proportional voltage. This analog voltage can be sensed by the Arduino and convert it to the appropriate current value. Arduino analog inputs can be used to measure DC voltage between 0 and 5V. We can use this to build a voltmeter. The range over which the Arduino can measure voltage can be increased by using two resistors to create a voltage divider. The voltage divider decreases the voltage being measured to within the range of the Arduino analog inputs. Code in the Arduino sketch is then used to calculate the actual voltage being measured. This allows voltages greater than 5V to be measured.

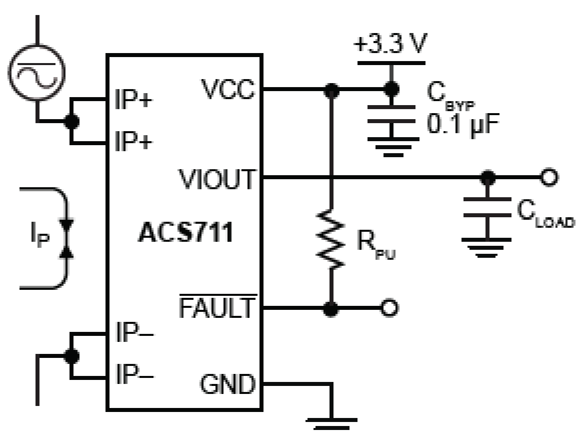

Figure 13: Current Measurement Ciurit

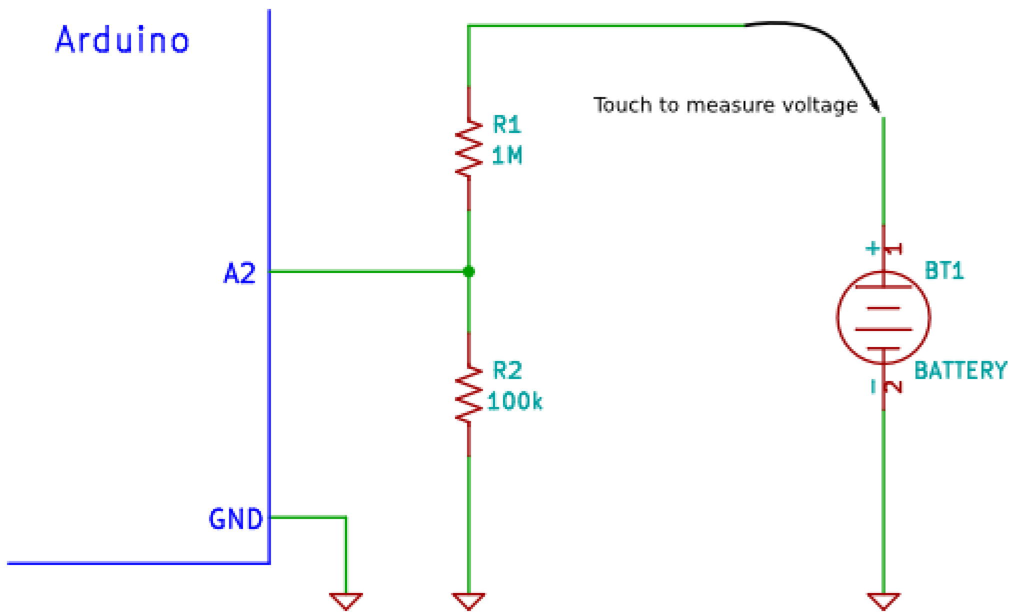

Figure 14: Voltage Measurement Circuit

2.3.4 Display System

This system contains a basic 16x2 character LCD display which is controlled by the Arduino. It could display the output voltage and the output current to the user.

3. Design Verification

3.1 Input Module

3.1.1 Battery

The battery voltage could be varied from 11.4 V (fully depleted) to 12.7 V (fully charged). The nominal voltage of the battery is 12 V.

3.1.2 AC Battery Charger

The battery charger could charge the battery safely to the nominal voltage of 12 V.

3.2 Output Module

3.2.1 DC/DC Converter

The converter met all the requirements we proposed. Table 1 shows the test result of our converter. The output voltage could be varied from 5 V to 48 V under 1 A output load condition. The efficiency could reach up to 80% and the minimum efficiency is 70% which satisfies our requirements. The output voltage ripple could be neglected due to the large output capacitance we used.

Table 1 Converter Test Results

Duty Ratio	V_{in}	I_{in}	P_{in}	V_{out}	I_{out}	P_{out}	Efficiency
31%	12	0.576	6.928	5.102	1.003	5.122	73.9%
46%	12	1.117	13.466	10.370	1.030	10.684	79.3%
55%	12	1.609	19.328	15.230	1.015	15.471	80.0%
62%	12	2.268	27.237	20.676	1.040	21.525	79.0%
67%	12	3.000	36.072	26.170	1.062	27.815	77.1%
70%	12	3.521	42.322	30.637	1.040	31.902	75.3%
73%	12	4.390	52.690	36.198	1.059	38.098	72.3%
75%	12	4.994	59.622	40.290	1.037	41.780	70.0%

3.2.2 Inverter and Transformer

The inverter met all the requirements. It could output the desired 30 V_{rms} AC voltage with the 3rd harmonic eliminated. The transformer could step up the AC output to the required 120 V_{rms}. The AC output of our system is shown in Figure 15. The frequency is 61.2 Hz and the RMS voltage is 115V. However, we could not reach the high output power condition due to low efficiency of both converter and inverter. The system efficiency is calculated by

$$\text{System Efficiency} = \eta_{converter} \cdot \eta_{inverter} \tag{12}$$

The average efficiency of our converter is 75% and the efficiency of inverter is 90% which gives us 67.5% of the total efficiency. Therefore, we must further improve the system efficiency to reach the high-power condition.

Figure 15: Inverter + Transformer Output Waveform with 3rd Harmonic Eliminated

3.3 Control Module

3.3.1 Microcontroller

The microcontroller could successfully generate five PWM signals as we required. It could generate a 100 kHz PWM wave with variable duty cycle that can be controlled by the rotary potentiometer. It could also generate four 60 Hz PWM waves for the four gate drivers of inverter circuit, with each wave has a specific phase shift. Figure 16 shows the PWM waveform generated for the converter. The frequency is 97.92 kHz with variable duty ratio. Figure 17 shows the PWM waveform generated for the inverter. Note that Yellow and blue are 180° phase shifted. Purple and green are 180° phase shifted. Yellow and purple are 30° phase shifted. The frequency of these four waves are 60 Hz.

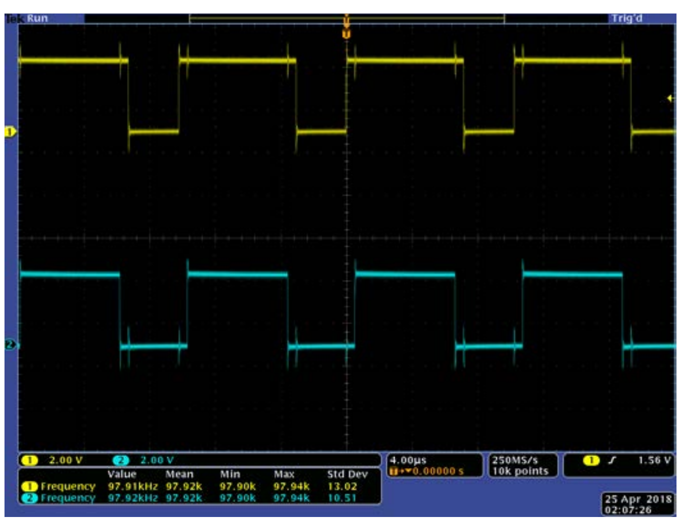

Figure 16: PWM Waveforms for Converter

Figure 17: PWM Waveforms for Inverter

3.3.2 User Interface

The rotary potentiometer could adjust the duty ratio from 20% to 75%.

3.3.3 Measurement System

The measurement system worked perfectly on the breadboard test during the mock demonstration. However, it failed when it was soldered on the perfboard for no reason. We didn't have enough time to replace the perfboard.

3.3.4 Display System

The LCD could display all the information sent by the Arduino.

4. Costs

4.1 Parts

Table 2 shows the gross parts costs of our project.

Table 2 Parts Costs

Part	Manufacturer	Retail Cost ($)	Quantity	Total Cost ($)
Gate Driver	Infineon Technologies	3.71	6	22.26
C2000 Microcontroller	Texas Instruments	17.7	1	17.7
Power MOSFET	STMicroelectronics	4.202	10	42.02
Inductor	Bourns Inc.	8.61	6	51.66
Schottky Diode	Microsemi Corporation	3.93	3	11.79
1000µF Capacitor	Nichicon	0.618	16	9.888
330µF Capacitor	Nichicon	0.931	10	9.31
LCD Display	SparkFun	24.95	1	24.95
Rotary Potentiometer	Precision Electronics Corporation	9.58	1	9.58
Current Sensor	Allegro MicroSystems	26.25	2	52.5
Enclosure Box	Hammond Manufacturing	73.65	1	73.65
Lead-acid Battery	Panasonic	48.47	1	48.47
Arduino	Arduino	23.38	1	23.38
Transformer	Hammond Manufacturing	75.6	1	75.6
Battery Charger	BatteryMINDer	44.99	1	44.99
DC Converter	GEREE	9.16	1	9.16
Outlet	Leviton	5.95	1	5.95
PCB	PCBWay	-	10	130
Total				**662.86**

4.2 Labor

Table 3 shows the estimated labor costs of our project.

Table 3 Labor Costs

Team Member	Hourly Rate ($/Hr)	Hours	Total Cost ($)
Zhuohang Cheng	40	150	15000
Zihao Zhang	40	150	15000
Total			**30000**

Therefore, our total investment costs will be

$$\text{Total Costs} = 662.86 + 30000 = 30662.86 \tag{13}$$

5. Conclusion

5.1 Accomplishments

Most of the high-level requirements specified for this project are mostly accomplished. The battery packs could draw power from the wall plug with the battery charger. With the DC power supply from the battery, the system could generate stable DC power ranges from 5V 1A to 48V 1A. The system could also convert the DC power from the battery to AC power ranges from 60Vrms to 120Vrms. The voltage and current of DC output of the system are measured and displayed to LCD screen.

However, the solar panel is not implemented for charging the system. Also, the AC output of 120Vrms could not reach 1A as we promised in the documentation.

5.2 Uncertainties

As stated above, the requirement of system to output 120Vrms AC power could be achieved, but the output could not stable at 120Vrms and continue increasing. This is probably due to efficiency of the system as well as the MOSFET characteristics. The efficiency of the system to convert 12V DC power to 120Vrms AC power is around 30%, which requires to draw large amount of current (around 5A) from the supply. The current is large enough to heat up the MOSFET reducing its efficiency. Therefore, the current would keep increasing and so does the output voltage. Although we tried to add cooling system into the circuit and replace a few components with smaller equivalent series resistance and higher ratings to improve the efficiency, we could not truly stabilize the output voltage at 120Vrms. This would require further implementation and research.

Also, the measurement circuit works perfectly on the breadboard but fails when it is soldered onto the perfboard. Soldering mistakes might be the reason, but we didn't have time to resolder it on another perfboard check.

5.3 Ethical considerations

Throughout the whole construction of the project, we strictly follow IEEE Code of Ethics in accepting the personal obligation to our profession.[6] As the code stated,

> *"To hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, and to disclose promptly factors that might endanger the public or the environment."*

When we decided to use lead-acid battery in this project, we carefully revealed the harms and dangers of using lead-acid battery in Design Documentation. We also appended information about how to correctly recycle lead-acid battery for human and environment health and welfare.

Also, as the code stated,

> *"To maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations."*

We performed simulation on LTSpice before we could do the on-board testing. Also, since we are dealing with high power that could cause severer damage on human body, protections like wearing rubbers and avoiding contact with the circuit during testing were strictly performed. Whenever problems occur during testing, power supply would be cut off as soon as possible.

5.4 Future work

Several implementation could be performed for future development of this system.

For overall design, PCBs could be designed more compactly and microcontroller chip could be integrated into the PCB to reduce the size of the system for portability. Also, solar panels with charging system could be integrated in the system for variable charging method as promised in high-level requirement. The battery pack with larger capacity could be selected for better endurance and that with smaller capacity could be chosen for portability.

For technical aspect, the efficiency of this system could be continue optimizing. This could be achieved by replacing components with smaller equivalent series resistance and higher ratings or try to change the design of the circuit as buck-boost converter instead of SEPIC converter.

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Appendix A Requirement and Verification Table

Table 4 System Requirements and Verifications

DC/DC Converter:

Requirement	Verification	Verification status (Y or N)
1. The converter must be able to handle a variable input voltage range (12 - 12.8 V).	1. Adjust the input voltage from 12 V to 12.8 V and change the duty ratio by hand to verify that the output voltage is constant all the time.	Y
2. The converter must be able to output a variable DC voltage (5 -48 V).	2. With constant input voltage, adjust the duty ratio to verify that the output voltage can vary from 5 V to 48 V.	Y
3. The converter must be able to handle a maximum current of 1 A.	3. Connect a 1 A load in the output end and operate the converter for several minutes to verify the operation status of the converter.	Y
4. The efficiency of this converter must be no less than 70%.	4. Calculate the output efficiency to verify that the efficiency of this converter is larger than 70%.	Y
5. The output voltage ripple must be less than 5%.	5. Probe the output voltage waveform to verify that the output ripple is less than 5%.	Y

DC/AC Inverter:

Requirement	Verification	Verification status (Y or N)
6. The inverter must be able to output an AC voltage of 30 $V_{rms.}$	6. Adjust the input DC voltage from 5 V to 48 V to verify that the inverter is able to output an AC voltage waveform	Y
7. The inverter must have a THD as low as possible (ideally, less than 5%).	7. Probe the output waveform to verify that the 3rd harmonic is eliminated.	Y

Microcontroller:

Requirement	Verification	Verification status (Y or N)

8. The microcontroller must be able to output multiple PWM signals to control the inverter switches.	8. Probe the output PWM waveform of the microcontroller to verify that each pair of PWM signal has a 180-degree phase shift.	Y
9. The microcontroller must be able to generate PWM signal with controllable duty ratio using rotary potentiometer for the SEPIC DC converter.	9. Probe the output PWM waveform of the microcontroller and rotate the rotary potentiometer to verify that the duty ratio would change according to the rotation.	Y

Battery Measurement System:

Requirement	Verification	Verification status (Y or N)
10. The system must be able to measure the output DC voltage from 5 V to 48 V.	10. Probe the output of DC/DC converter to multimeter and change the output voltage to see if the measurement accords with the multimeter.	Y
11. The system must be able to measure the output current with a maximum value of 1 A.	11. Probe the output of DC/DC converter to multimeter and change the voltage to output 1A current to see if the measurement accords with the multimeter.	Y
12. The system must be able to measure the temperature from 0 to 60 degrees Celsius. The measuring error must be less than 5 %.	12. Use thermometer to see if the measurement agrees.	N
13. This system must be able to display the correct measurement on the LCD screen.	13. Program the microcontroller to display some test value to verify that the system can display the same value.	Y

User Interface:

Requirement	Verification	Verification status (Y or N)
14. The user can change the output power mode using the control panel.	14. Use the control panel to change the output power mode to verify that the output voltage can be either AC or DC.	N
15. The output voltage level can be controlled by the control panel.	15. Measure the output voltage and current with a multimeter, set different output voltage using the	Y

		control panel to verify that the output voltage can be varied from 5 V to 48 V DC, 120 V AC.	