BI-DIRECTIONAL FLYBACK DC-DC CONVERTER FOR THE DC HOUSE PROJECT

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ABSTRACT

The DC House project strongly relies on renewable energy sources to provide power to the house for various loads. However, when these sources are unable to provide power at a certain time, a back-up energy source from a battery must be readily available to fulfill the house's power needs. This thesis proposes a bi-directional flyback power converter to allow a single-stage power path to charge the battery from and to discharge the battery to the DC House 48 V system bus. The design, simulation, and hardware prototype of the proposed flyback bi-directional converter will be conducted to demonstrate its feasibility. Results from a 35W prototype demonstrate the operation of the proposed converter for both charging and discharging purposes.

Keywords: *Bidirectional Converter, Battery Charging, Flyback Converter*

1. INTRODUCTION

According to the Census Bureau, the world population has steadily increased from 2,557,628,654 people in 1950 to 7,095,217,980 in 2013 [1]. Because of increasing population in the world, energy demand in developing nations is expected to rise 65% by 2040 compared to 2010, reflecting growing prosperity and expanding economies [2]. In response to the population growth, a greater demand for electricity will be seen from all developed and rural countries [2]. Figure 1 reflects the projected energy demand from 2010 to 2040 for different continents and countries.

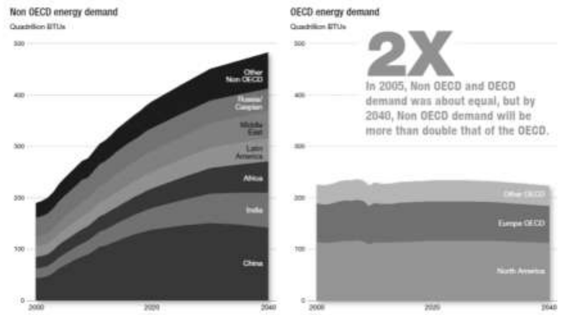

Figure 1. Projected Energy Demand for Different Continents and Countries by 2040 [2]

For the next 30 years, electricity generation represents the largest energy use across four different sectors: industrial, transportation, electricity generation, and residential/commercial. However even with advancements in science and technology, according to the International Energy Agency (IEA), around 1.3 billion people today still do not have access to electricity [2]. Therefore, in order to help combat the dependency on electricity, renewable energy has become a larger priority in order to help provide for those that do not have electricity especially in areas inaccessible by the utility grid. According to the US Energy Information Association, renewable energy accounts for 32 percent of the overall growth in electricity generation from 2011 to 2040 [3]. The ability to provide electricity power through both new methods and renewable energy creates an opportunity for new technology to meet the electricity demand such as the DC House Project.

The DC House project started in 2010 by California Polytechnic State University in hopes of creating an operating house whose electricity is provided from DC power. The purpose of the DC House project is to help those in third-world countries receive electricity in locations that are not accessible to grid generation. In our predominately AC system, small-scale renewable energy sources are generally putting out DC power and hence require intermediate energy conversion to AC in order to be accessible to the consumer [4]. However, converting from DC power to AC power may imply extra cost for equipment to implement such a system as well as potentially increase the amount of power loss that the system experiences and thus reducing the overall efficiency of the system. The DC House attempts to bypass such a power conversion in order to provide enough energy for typical household items without the reliance of AC power.

The initial study and modeling of individual DC powered home including the design for several possible DC power sources was reported in references [5] to [8], and [10]. The preliminary design of the multiple-input-single-output (MISO) DC-DC converter that ties all the outputs of the possible DC energy sources to a single output which provides the main DC bus voltage that feeds power to the DC house was presented in [9]. For the battery charging component of the DC House, a bidirectional DC-DC converter is needed to allow power flow to go from the DC Bus to the battery (charging) and from the battery back to the DC Bus (discharging).

A majority of DC-DC converters provide current in a unidirectional fashion by having a single path for current to flow from the input source to the load. For example, a non-isolated topology known as the Buck converter provides current from the input source to the output through the MOSFET switch, the inductor, and the free-wheeling diode during the time when the MOSFET switch is off. Because of the inability for the switch and the diode to carry current in the reverse direction from the load to the input voltage source, the Buck converter is a unidirectional DC-DC converter.

Bi-directional DC-DC converters fall into a generic circuit structure illustrated in Figure 2 which is characterized by current or voltage being fed from one side to the other [16]. Based upon the magnitude of the voltage and current as well as the placement of the energy storage items, the bi-directional DC-DC converter can either operate as a Buck converter by stepping down a higher voltage to a lower voltage or as a Boost converter by stepping up from a lower voltage to a higher voltage.

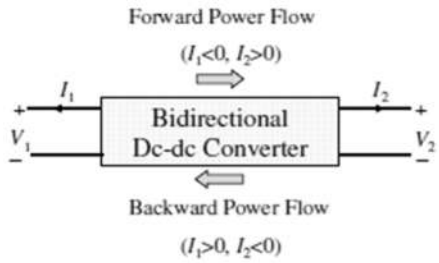

Figure 2. Generic Circuit describing Power Flow of a Bi-directional DC-DC Converter [16]

In order to allow bi-directional power flow between two energy storage items with a DC-DC converter, a secondary switch and a reverse diode on the main commutating switch is needed for a uni-directional converter. Bi-directional DC-DC converters have been used in applications for charging batteries, electrical vehicle motor drives, and interruptible power supplies. Such topologies that have been used include a non-isolated topology such as the buck-boost and isolated topologies such as the half-bridge, the full-bridge and the flyback. The non-isolated buck-boost is an advantageous topology because the converter does not require the transformer to be used as an energy transfer or energy storage component and for applications that do not require isolation between the input and output [17]. Despite the lack of a transformer, the buck-boost topology relies heavily on soft switching techniques such as zero voltage switching (ZVS) or zero current switching (ZCS) in order to compensate for high voltage spikes seen by switching MOSFETs and inductors [17]. The half-bridge and full-bridge topology are suitable for high power applications and high voltage applications but require large amounts of components and use of snubbers, making the design portion of the converter complex [18]. The flyback topology on the other hand uses the transformer as an energy storage device, but the topology yields low costs, good transient response, and low amount of components [19].

As long as the requirement of allowing two paths of current flow is satisfied, any topology, non-isolated or isolated, can be converted into a bi-directional topology. Because of the low amount of required components, the use of the transformer to compensate for low duty cycle, and the availability of controller chips for commercial purchase, the flyback topology will be chosen for the proposed bi-directional DC-DC converter. This paper presents the use of the flyback topology for the bi-directional DC-DC power converter. The bi-directional power converter is needed for the battery system used in the DC House project.

2. TOPOLOGY AND DESIGN REQUIREMENTS

Generally speaking, any uni-directional converter can be turned into a bi-directional converter by adding an additional secondary switch on the output diode and a reverse diode on the main commutating switch. Due to its lower cost, low component count, good transient response, and the ability to use the turns ratio to increase the duty cycle of the overall system, the flyback topology will be used for the proposed DC House bi-directional converter [20]. Two flybacks will be chosen to regulate the discharging and charging stages of the bi-directional converter. Figure 3 shows the power stage of the dual flyback with the reverse diodes placed across the switches to make the converter bi-directional. Two controller chips will be selected based upon the output voltage and power requirements defined in this chapter.

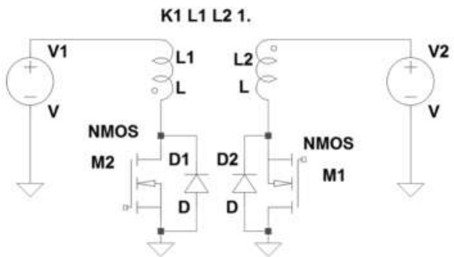

Figure 3. Dual Flyback Power Stage of Bi-directional Converter

Efficiency is an important aspect of the bi-directional converter because of the lifetime of the car battery as well as reducing the amount of switching losses from two separate flyback topologies. Therefore, the proposed design is expected to operate with greater than 80% efficiency at maximum load for both the charging and discharging stage. Although the integrity of the output voltage is not necessarily important since the battery will be charged using constant current, the output voltage ripple will be expected to be less than 5% of the 48V output for the discharging stage and the 12.5V output for the charging stage. Line and load regulations will be less than 5% for both the discharging and charging stage of the bi-directional DC-DC converter. Table 1 summarizes the design requirements for the proposed bi-directional converter.

Table 1. Specifications of the Bi-directional DC-DC Converter

	Charging Stage	**Discharging Stage**
Input Voltage	48V ± 5%	(11V-13V), 12V Nominal
Output Voltage	12.5V	48V
Maximum Output Current	2A	1A
Maximum Output Wattage	25W	48W
Line Regulation	5%	5%
Load Regulation	5%	5%
Output Voltage Ripple	5%	5%
Efficiency at Full Load	≥ 80%	≥ 80%

3. SIMULATION RESULTS

Because of the power constraint, the LT3748 controller chip is chosen because of its power rating as well as its ability to derive information from the output voltage based upon the primary-side flyback pulse waveform [21]. The controller features a boundary mode control method, where the output voltage can be derived from the transformer primary voltage when the secondary current is almost zero. Using this feature reduces the size of transformer, excludes subharmonic oscillations, and improves load regulation [21]. Figure 4 shows the complete 48V to 12V charging flyback with calculated resistors and capacitors for each pin of the controller chip.

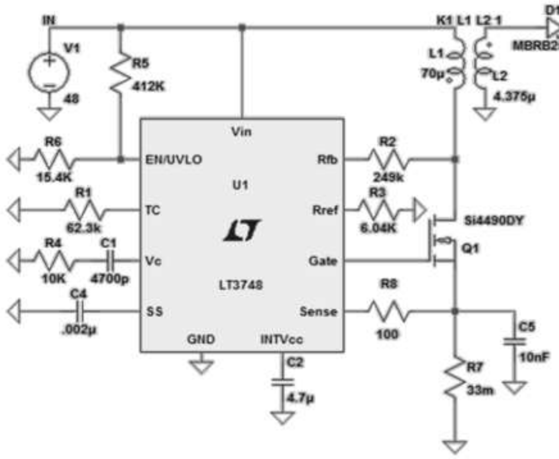

Figure 4. 48V to 12V Charging Flyback with LT3748 Controller Chip

Figure 4 details the output voltage ripple of the charging flyback with a full load of 2A. The average voltage is determined to be 12.6V, with a peak to peak ripple voltage of 0.4V or 3% of the output voltage. Figure 5 shows the voltage of the current sense pin of the LT3748 controller when the charging flyback is supplying power for full load. Boundary conduction mode can be seen as the voltage of the current sense pin drops to zero. Since the voltage of the current sense pin is below the threshold voltage of 100mV, the MOSFET is able to be turned on and off to achieve the output voltage. The line regulation of the charging flyback is calculated to be approximately 0%, while line regulation is 0.83%. Figure 7 shows the charging efficiency of the system ranging from a minimum load current of 0.4A up to full load current of 2A in increments of 0.4A.

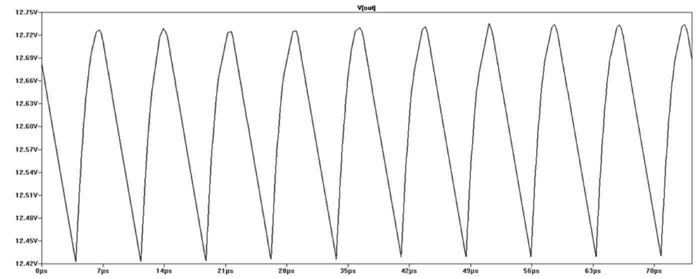

Figure 5. Simulated Output Voltage Peak-to-Peak Ripple at Full Load (2A) for Charging Flyback

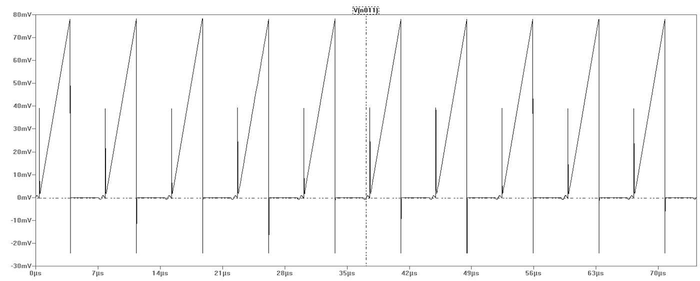

Figure 6. Simulated Voltage at Sense Pin at Full Load (2A) for Charging Flyback

Figure 8 shows the complete 12V to 48V discharging flyback with calculated resistors and capacitors for each pin of the controller chip. Figure 9 shows the output voltage ripple for the discharging flyback with a full load of 1A. The average voltage is observed to be 48.3V, with a peak to peak ripple voltage of 0.4V or 0.83% of the output voltage. Figure 10 shows the voltage of the current sense pin of the LT3748 controller when the discharging flyback is supplying power for full load. Figure 11 shows the efficiency of the discharging flyback from 0.2A to 1A load current in increments of 0.2A. The line and load regulations of the discharging flyback are 0% and 1% consecutively.

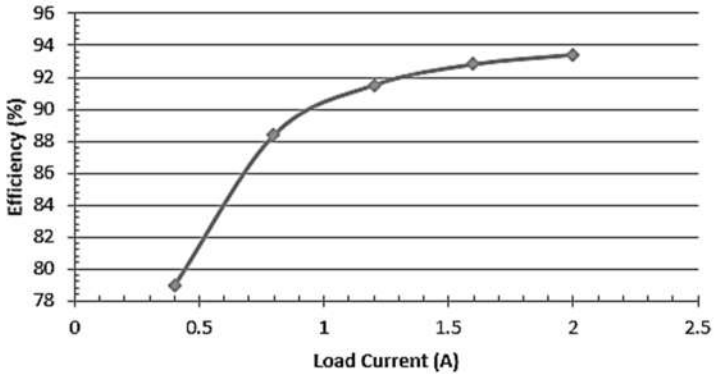

Figure 7. Efficiency of the Charging Flyback with Varying Load Current from 0.4A to 2A

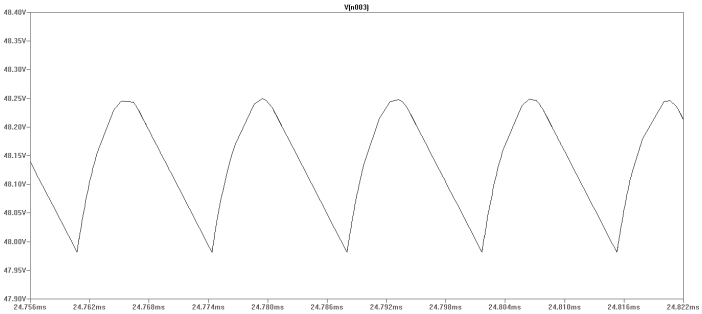

Figure 8. Simulated Output Voltage Peak-to-Peak Ripple for 1A Load for Discharging Flyback

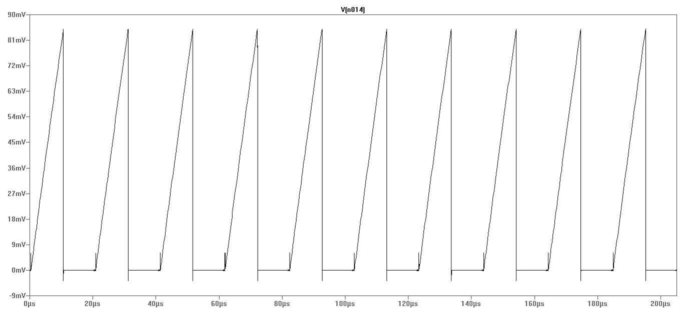

Figure 9. Simulated Voltage at Sense Pin at Full Load (1A) for Discharging Flyback

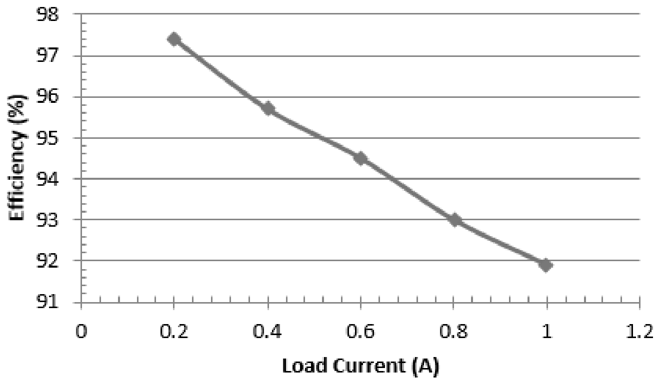

Figure 10. Efficiency of Discharging Flyback vs. Varying Load Current

Figure 11 shows the entire bi-directional DC-DC converter design with the complete LT1716 control scheme.

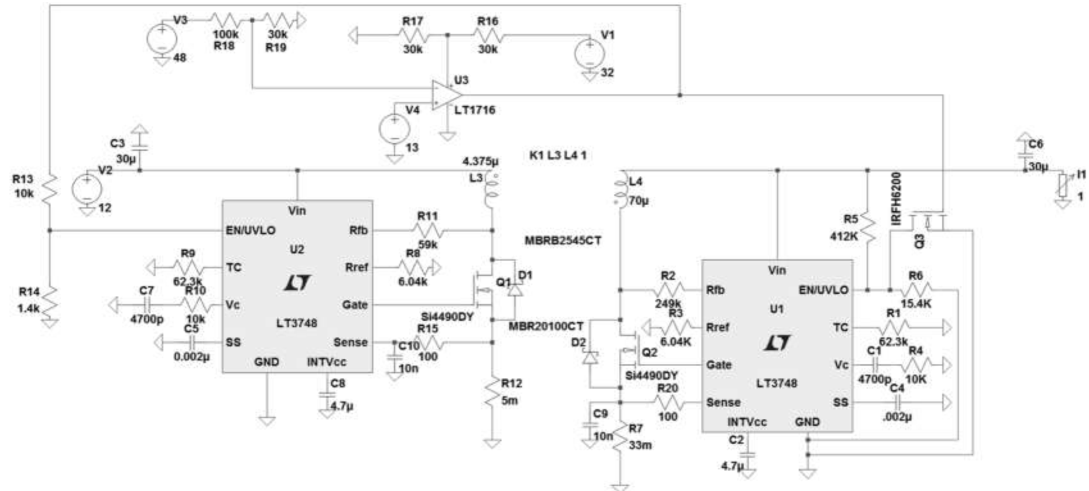

Figure 11. Full Bi-directional DC-DC Converter LT Spice Design

2. HARDWARE RESULTS

The bi-directional DC-DC converter was designed using a PCB layout program provided by Express PCB. Common-practice rules for design were followed, including minimum trace spacing and proper trace width dependent upon average current seen by each trace. The PCB layout was designed using 4 layers: top copper layer, power layer, ground layer, and bottom copper layer. Figure 12 shows the entire PCB design with the top layer traces and bottom layer traces. The hardware lab test setup is depicted in Figure 13.

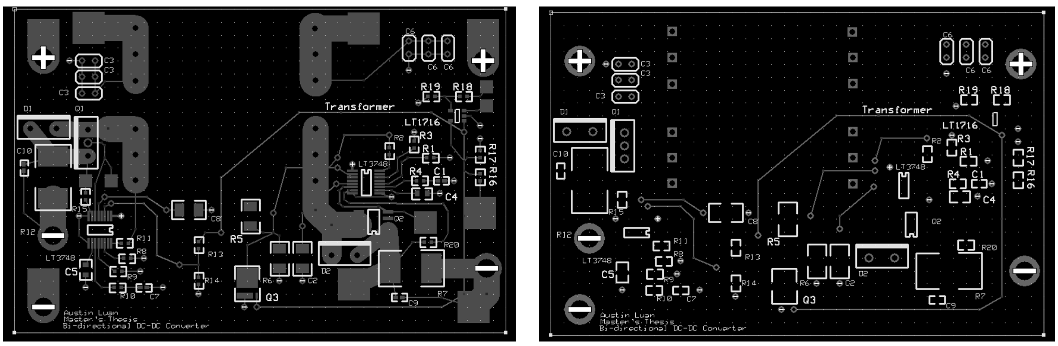

Figure 12. Top Layer with Silkscreen and Bottom Layer of PCB

The charging flyback must be able to supply a full load of 2A at a regulated voltage of 12.5V. Thus, the flyback will be tested in percent of load increments to monitor the efficiency of the flyback. Also, the output voltage ripple will be observed as well as the gate voltages of both flyback controllers to prove that while the charging flyback is commutating, the discharging flyback is disabled. Load regulation was measured to be 2.6% while the line regulation was 0.252%. The load and line regulations for the charging flyback meet the requirement of less than 5%. Figure 14 shows the efficiency of the charging flyback of the bi-directional DC-DC converter over percentage of load. Figure 15 shows the output voltage peak-to-peak ripple of the charging flyback at full load conditions calculated to be 16%.

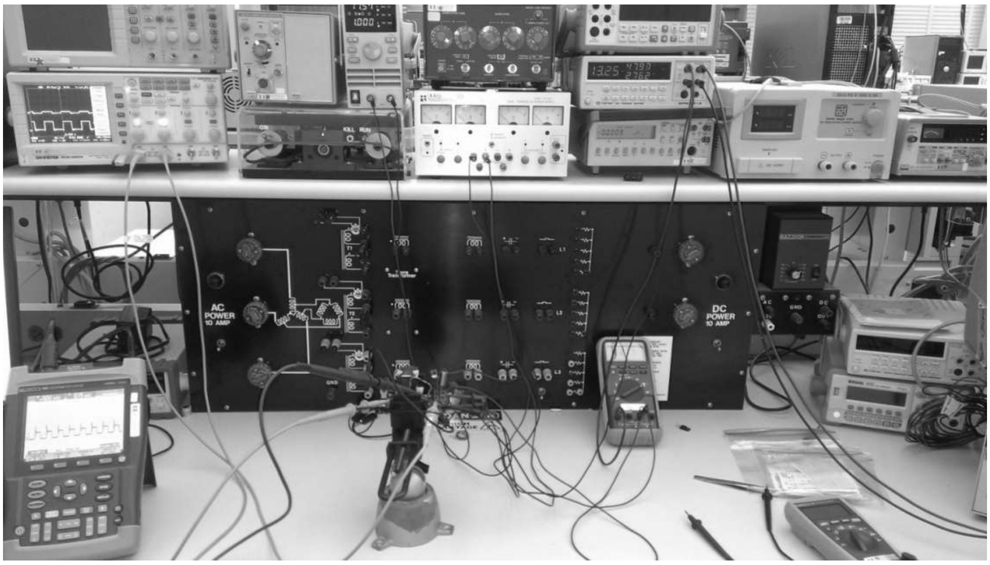

Figure 13. Test Set-up and Equipment Used for Testing Bi-directional DC-DC Converter

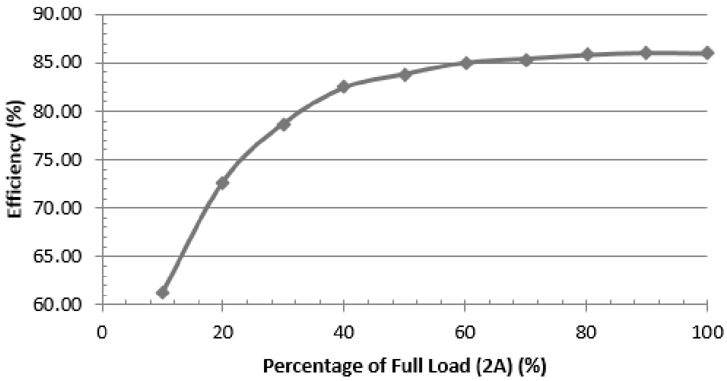

Figure 14. Efficiency vs. Percent Load for Charging Flyback

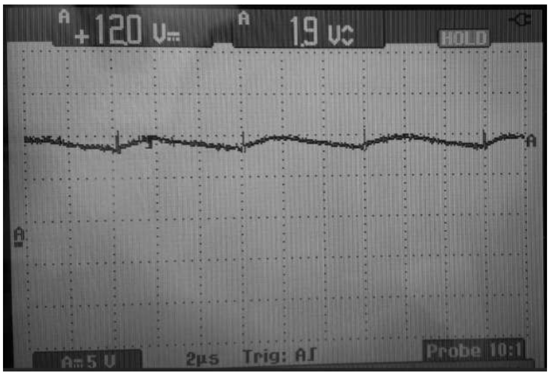

Figure 15. Output Voltage Peak-to-Peak Ripple of Charging Flyback at Full Load Conditions

For the discharging mode, the load regulation was calculated to be 2.87%, and the line regulation was calculated to be 1.84%. The efficiency plot is shown in Figure 16. Figure 17 shows the output voltage peak-to-peak ripple of the discharging flyback at full load conditions. With a measured peak-to-peak voltage of 4V, the output voltage ripple is calculated to be 8.2%. Compared to the simulation results, hardware results such as the efficiency, line regulation, load regulation, and output voltage of the discharging flyback meet the requirements. The peak-to-peak output voltage of the discharging flyback at full load conditions is higher than the required 5%.

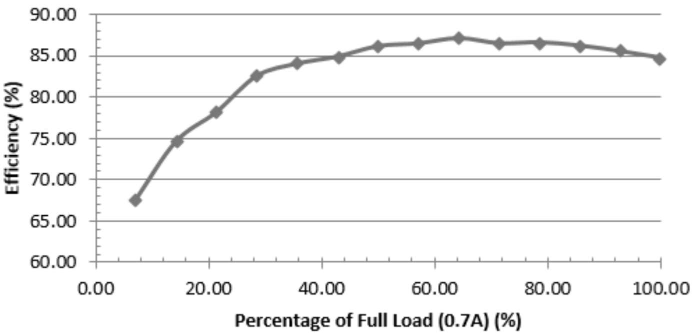

Figure 16. Efficiency vs. Percent Load for Discharging Flyback

Figure 17. Output Voltage Peak-to-Peak Ripple of Discharging Flyback at Full Load Conditions

Table 2 shows a summary of the hardware results and simulation results compared to the design requirements.

Table 2. Design Requirements Summary after Simulation and Hardware Results

	Charging Flyback			**Discharging Flyback**		
	Design Requirement	**Simulation Results**	**Hardware Results**	**Design Requirement**	**Simulation Results**	**Hardware Results**
Input Voltage	48V	48V	48V	12V	12V	12V
Output Voltage	12.5V	12.6V	11.88V	48V	48.3V	48.8V
Full Load Current	2A	2A	2A	1A	1A	0.7A
Full Load Output Wattage	25W	26.6W	24W	48W	53W	34W
Line Regulation	5%	0%	0.25%	5%	0%	1.8%
Load Regulation	5%	0.7%	2.6%	5%	0.2%	2.9%
Output Voltage Ripple	5%	2.4%	16%	5%	0.3%	8.2%
Efficiency at Full Load	≥ 80%	95 %	86%	≥ 80%	92%	85%

4. CONCLUSION

The bidirectional converter did meet most of the target electrical constraints. During hardware implementation, the converter was able to provide a single path power flow for both the discharging and charging flyback using the LT1716 control scheme. For the charging flyback, the bidirectional converter was able to operate from an input voltage ranging from 11V to 13V at excellent line regulation. The charging flyback also produced an efficiency of 86% with a total output power of 24W at full load conditions of 2A. The charging flyback was also able to maintain load regulation from a minimum load of 0.2A up to a full load of 2A.

For the discharging flyback, the bi-directional converter was able to operate from an input voltage ranging from 46V to 50V at excellent line regulation. The discharging flyback also produced an efficiency of 85% with a total output power of 34W at full load conditions of 0.7A. The discharging flyback was also able to maintain load regulation from a minimum load of 0.05A up to 0.7A.

Although the concept of the bi-directional converter is feasible, further improvements can be done in the future such as a better control scheme, larger output power capability, and implementation of the converter with the DC House system. The current control scheme does allow the converter to switch between the discharging and charging flyback. However, the exchange between each flyback is centered on the set voltage of 11V. Thus, the charging and discharging flybacks can only operate between the battery voltages of 11V to 11.1V. An improved control scheme would allow the bi-directional converter to operate for a wider battery voltage range. Currently, the proposed bi-directional converter is able to supply 35W using the flyback topology. Using other topologies or improving on the flyback design of the converter can help achieve the ultimate goal of an output power of 150W. Protection schemes such as fuses or current limiting applications on the battery side are needed to preserve not only the battery but the 48V DC bus line that feeds into the DC House.

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A Single Board Buck and Boost Bidirectional DC-DC Converter for DC House Energy Management System

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ABSTRACT

This paper entails the design, construction, and testing of a single board buck and boost bidirectional DC-DC converter to reduce components and improve efficiency. The approach aims to replace the previously designed converter which made use of a separate buck converter and boost converter boards. The bidirectional converter will eventually reside in the Energy Management System (EMS) of the DC House system. This new converter 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. Analysis of the bidirectional DC-DC converter shows high efficiency especially at larger load currents. Testing of the system demonstrated its ability to successfully direct power between the 48V DC bus and load and the 12V battery.

Keywords: *Bidirectional Converter, Energy Management System, DC House Project*

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.

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 1 shows the basic block diagram of the whole DC House system.

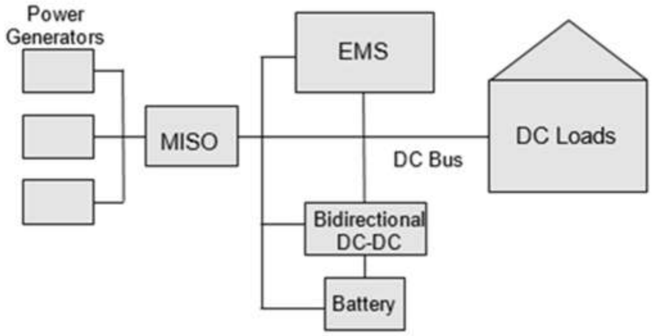

Figure 1. DC House Block Diagram Overview

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.

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.

2. TOPOLOGY AND 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 2 shows the basic block diagram with these inputs and outputs.

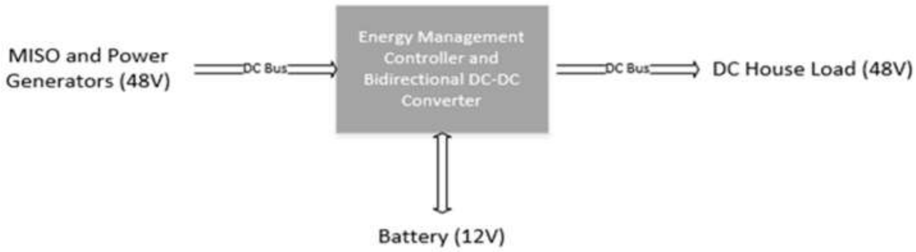

Figure 2. DC House EMS Block Diagram

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 the Multiple Input Single Output (MISO) converter, 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 more detailed block diagram of Figure 3.

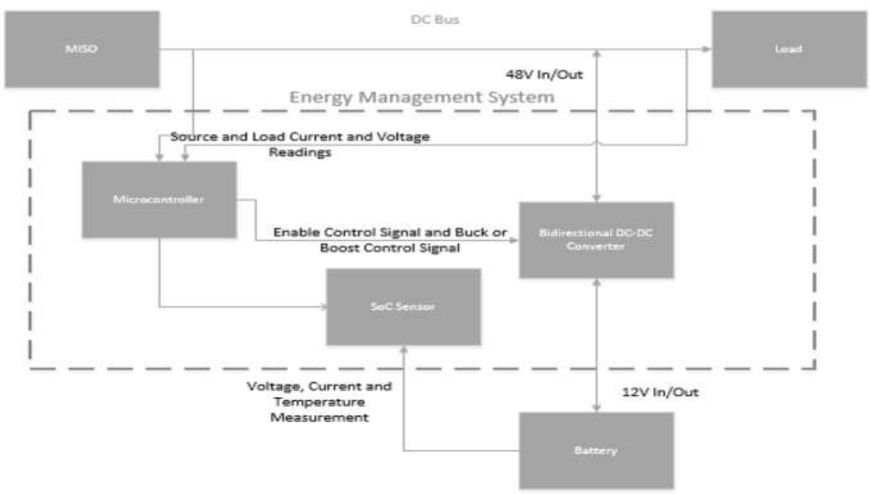

Figure 3. Detailed DC House EMS Block Diagram

3. DESIGN

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.

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 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).

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.

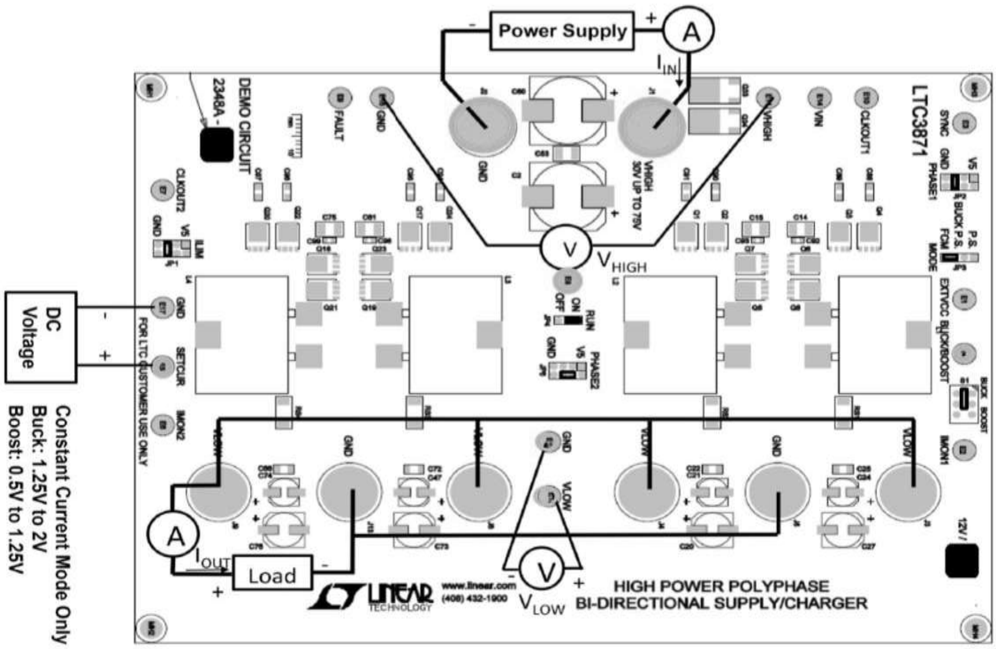

Figure 4. Bi-Directional DC-DC Converter Board and Connections

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. 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.

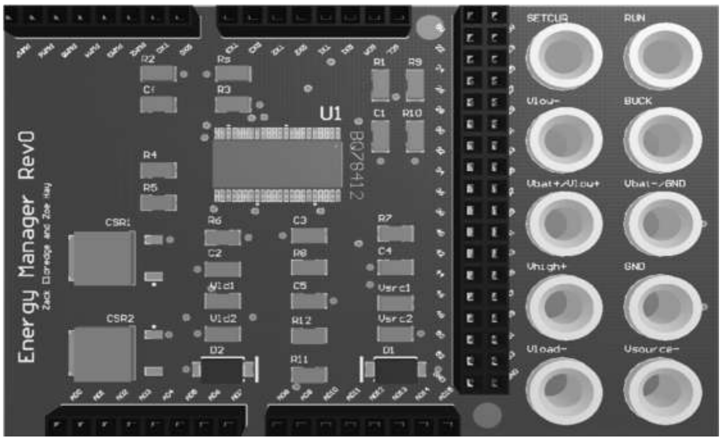

Figure 5. 3D PCB layout

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]. 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.

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 5 shows a three-dimensional rendering of the manufactured and soldered PCB.

4. HARDWARE RESULTS

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 6.

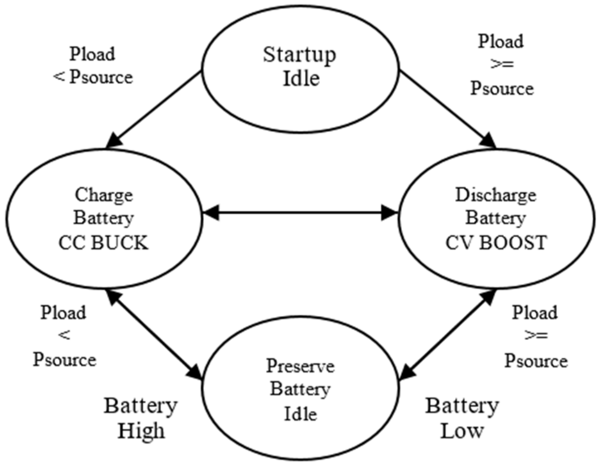

Figure 6. Simple State Diagram of Arduino Code

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 7 shows a picture of the populated PCB mounted on the microcontroller.

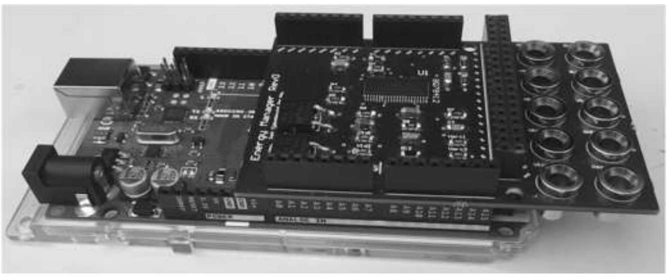

Figure 7. PCB and Arduino Microcontroller Setup

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. Figure 8 depicts the constructed enclosure.

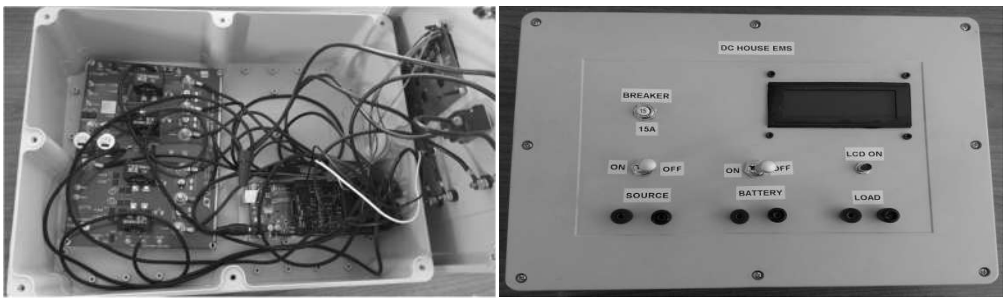

Figure 8. Fully constructed enclosure: inside (left) and outside (right)

The Bidirectional DC-DC converter was tested to determine its operating efficiency. 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 9. 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.

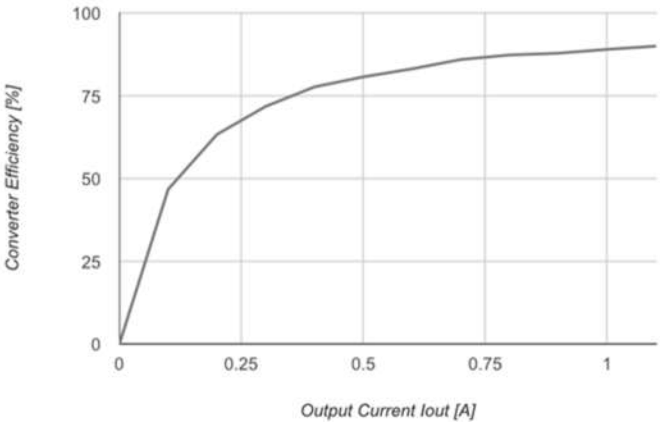

Figure 9. Efficiency of the Bidirectional DC-DC Converter Operating in Boost Mode

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 10. 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.

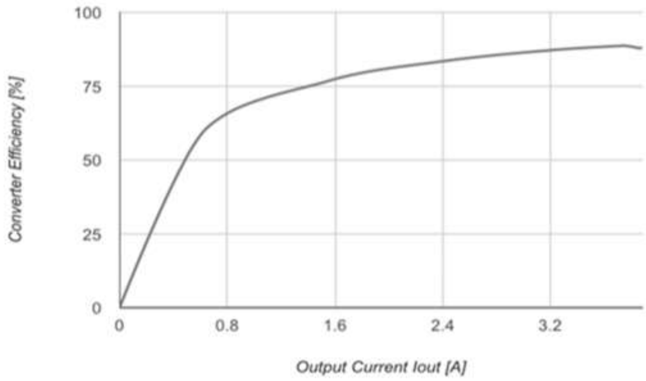

Figure 10. Efficiency of the Bidirectional DC-DC Converter Operating in Buck Mode

The system was tested using different setups depending on the mode of operation being simulated. Figure 11 shows the test setup for when the EMS directs power from the 12V battery to supply power to the 48V DC bus.

The power supply and electronic load were adjusted to emulate different conditions and control the mode of the converter.

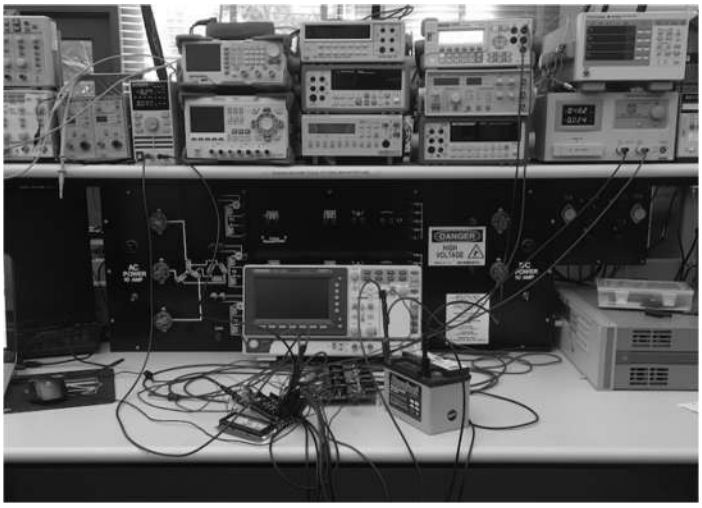

Figure 11. Efficiency of the Bidirectional DC-DC Converter Operating in Buck Mode

Table 1 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 1. 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

5. 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.

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. 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. 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.

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. 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.

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