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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.

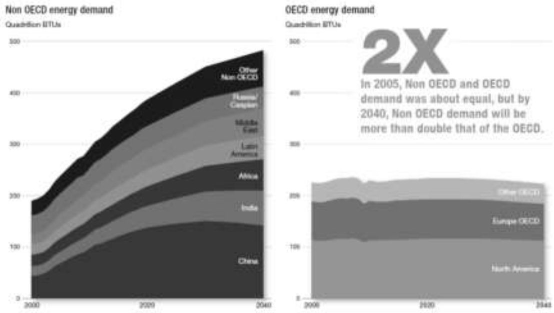

Figure 1. Projected Energy Demand for Different Continents and Countries by 2040 [2]

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.

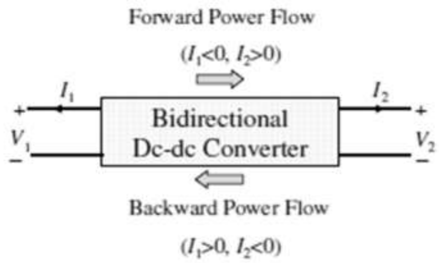

Figure 2. Generic Circuit describing Power Flow of a Bi-directional DC-DC Converter [16]

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.

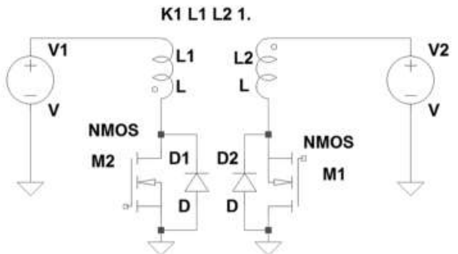

Figure 3. Dual Flyback Power Stage of Bi-directional Converter

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.

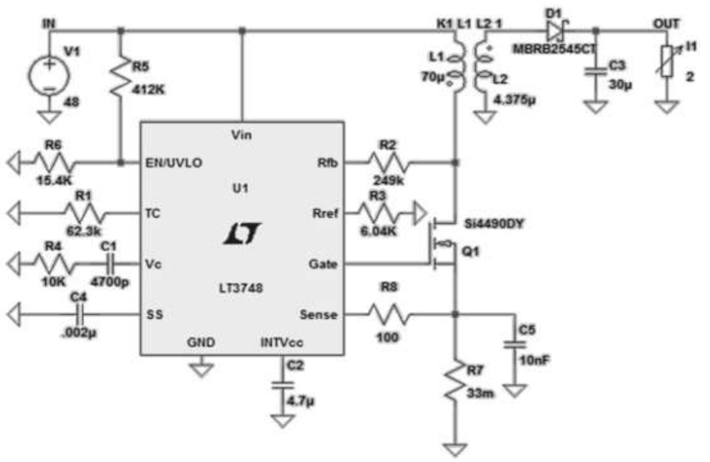

Figure 4. 48V to 12V Charging Flyback with LT3748 Controller Chip

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.

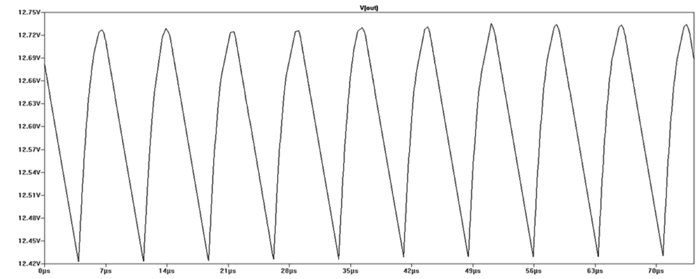

Figure 5. Simulated Output Voltage Peak-to-Peak Ripple at Full Load (2A) for Charging Flyback

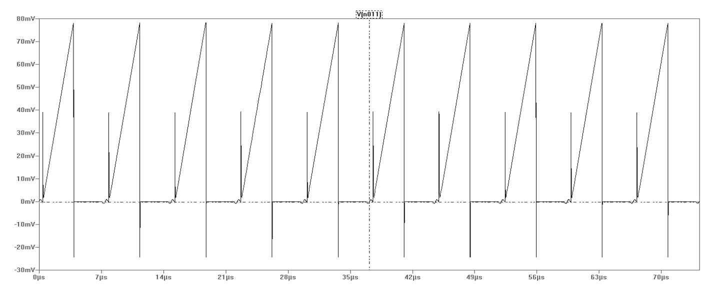

Figure 6. Simulated Voltage at Sense Pin at Full Load (2A) for Charging Flyback

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.

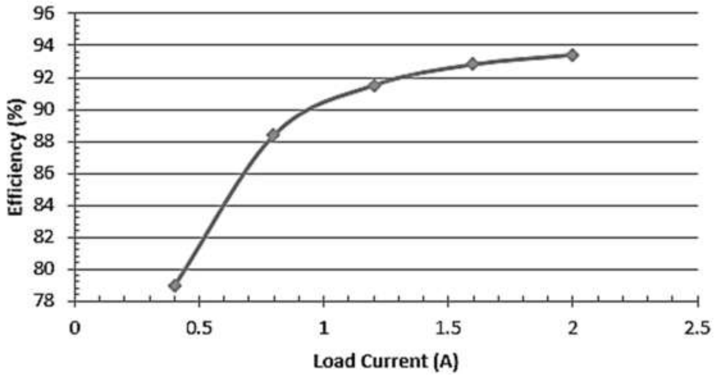

Figure 7. Efficiency of the Charging Flyback with Varying Load Current from 0.4A to 2A

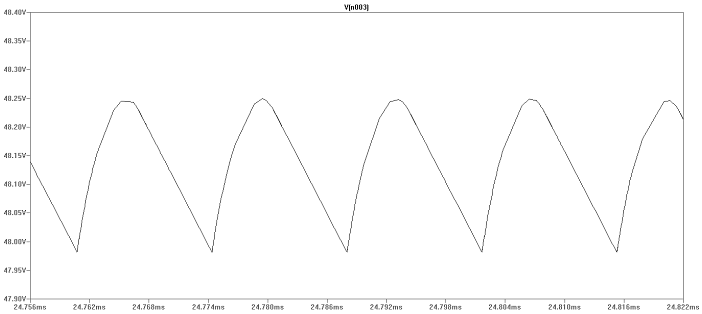

Figure 8. Simulated Output Voltage Peak-to-Peak Ripple for 1A Load for Discharging Flyback

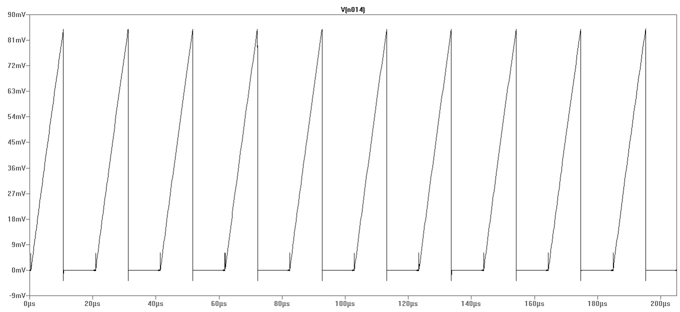

Figure 9. Simulated Voltage at Sense Pin at Full Load (1A) for Discharging Flyback

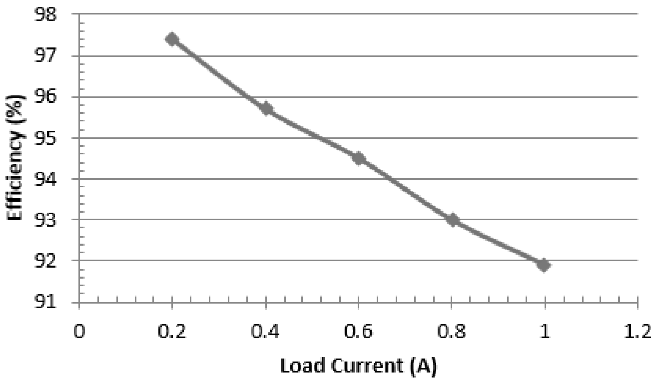

Figure 10. Efficiency of Discharging Flyback vs. Varying Load Current

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

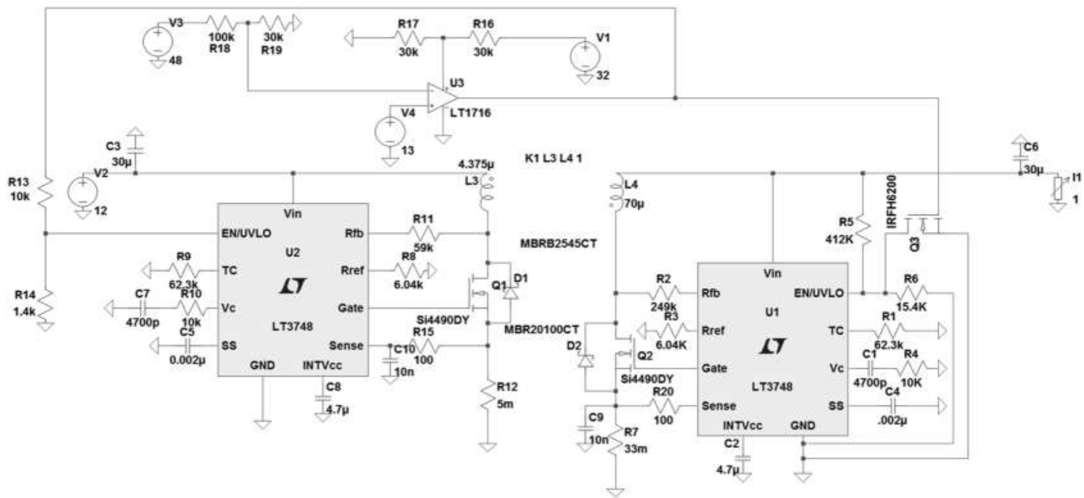

Figure 11. Full Bi-directional DC-DC Converter LT Spice Design

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.

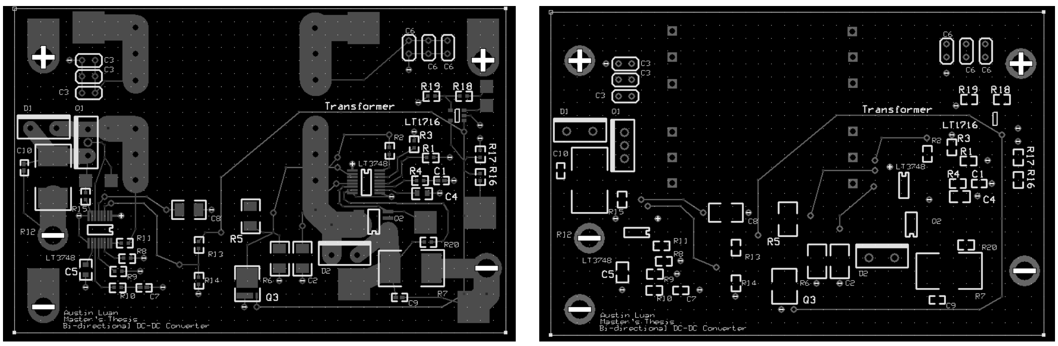

Figure 12. Top Layer with Silkscreen and Bottom Layer of PCB

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%.

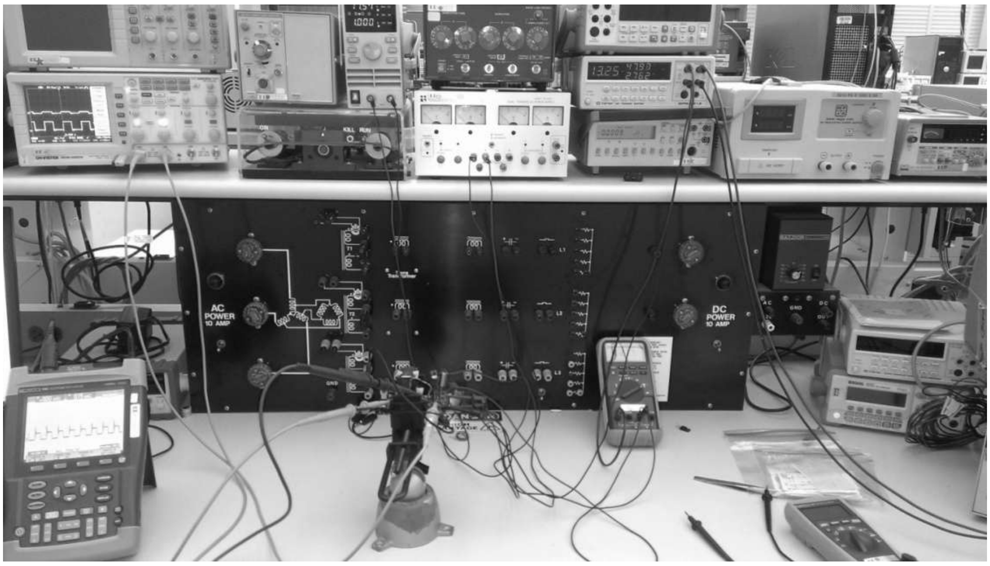

Figure 13. Test Set-up and Equipment Used for Testing Bi-directional DC-DC Converter

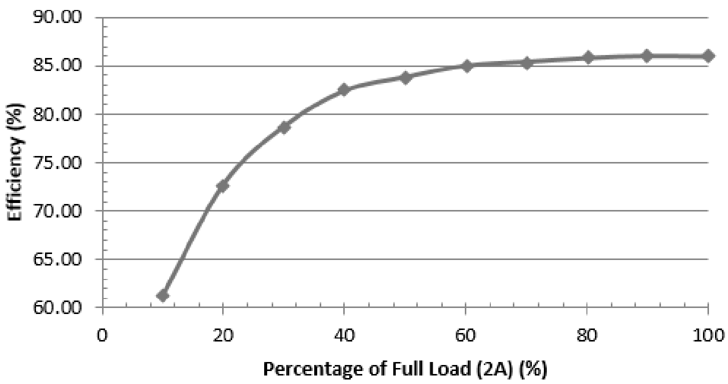

Figure 14. Efficiency vs. Percent Load for Charging Flyback

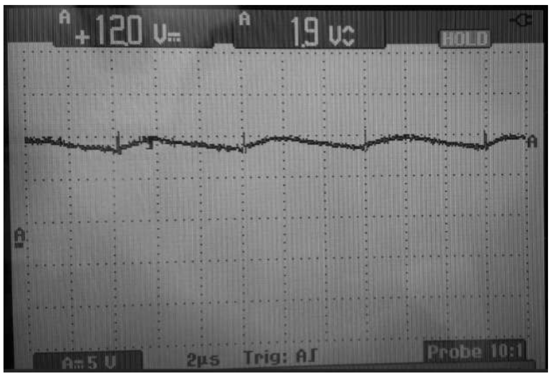

Figure 15. Output Voltage Peak-to-Peak Ripple of Charging Flyback at Full Load Conditions

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%.

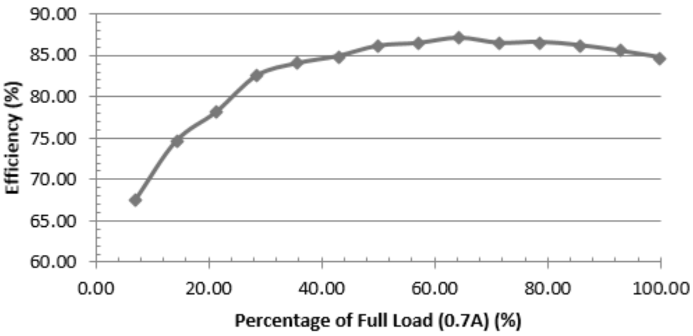

Figure 16. Efficiency vs. Percent Load for Discharging Flyback

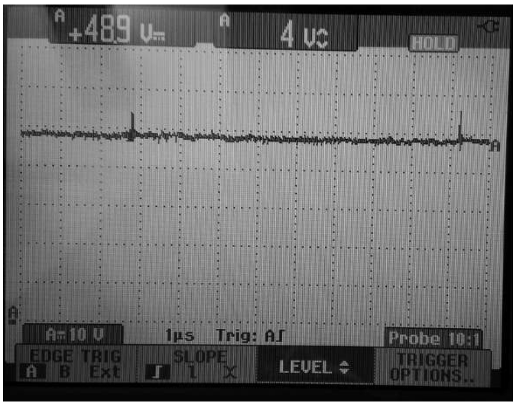

Figure 17. Output Voltage Peak-to-Peak Ripple of Discharging Flyback at Full Load Conditions

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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