Bi-Directional DC-DC Converter for the DC House Project

Abstract—This paper presents a project that was developed with the purpose of creating an efficient energy management system for the DC House project, with a centralized 12V battery system fed by a 48V Multiple Input Single Output Source (MISO). The energy management system will consist of a bidirectional DC-DC converter. During the day when the renewable sources produce enough energy to fulfill the load’s energy demand, the converter will make use of the excess energy by taking a 48V DC input and stepping it down to a 12V DC output in order to charge a 12V 100Ah battery. When renewable sources can no longer supply the energy required by the load the necessary energy will be pulled from the 12V battery. The converter at this time will take the 12V DC input from the battery and step it up to a 48V output connected to DC House load. The proposed design was tested using LTSpice simulation whose results showed that the converter can indeed provide the bi-directional power flow as desired. Simulation results showed that the proposed design was able to meet the less than 2% line and load regulation requirements. Furthermore, the efficiency of the proposed converter was measured to be around 85% at full load.

Keywords— Bidirectional DC-DC Converter, DC House, Energy Management System, Renewable Energy

I. INTRODUCTION

The DC House Project is a humanitarian project focused on providing energy to rural or secluded areas through the use of renewables and human powered generators [1]-[6]. While AC power is the most dominant form of electricity, many rural or secluded areas especially in third world countries do not have reliable access to AC power [7][8]. This issue makes or secluded areas especially in third world countries do not have reliable access to AC power. This issue makes AC power the most dominant form of electricity, many rural areas connected and provide a single output voltage to a DC bus [10]-[13]. The EMS system regulates the flow of electricity to charge or discharge the battery as renewable sources are inconsistent. The battery is charged and discharged through a bi-directional DC-DC converter. Fig. 2-1 shows the basic diagram of the DC House [1].

Referring to [5], the current EMS for the DC House uses a 48V bus and a 12V battery. Furthermore, the design tracks the state of charge (SoC) which can also monitor voltage, current, runtime-to-empty, and temperature of the battery. This design is for use with 12V Pb-Acid batteries. Based on the state of charge of the battery and the demand from the load, a microcontroller will direct the flow of electricity to either charge or discharge the battery. This is accomplished by controlling when the DC-DC converter is stepping the voltage down from 48V to 12V (buck mode) or stepping the voltage up from 12V to 48V (boost mode). Operating parameter values are displayed on a small LCD screen. To accommodate the charging and discharging of the battery, a bidirectional DC-DC converter was utilized using the Buck-Boost converter to control the direction of the power [5].

Many design changes can be implemented to improve the overall quality of the current EMS design. The previous design noted that the chip used in the design created a number of issues that limited how quickly the LCD screen could be updated and that it was nearing the end of production [13]. A more robust SoC chip would greatly improve the processing speed of the LCD. Another area of improvement is the price point. The DC House project is primarily geared towards humanitarian efforts, a low cost is ideal. The current design has a cost of $515, primarily due to the cost of the DC-DC converter board at $370. Finally, while the previous project displays the voltage and current values using the LCD screen, most consumers will not have the knowledge to understand what this means [14].

![Simplified DC House system block diagram.](image)

Fig. 1. Simplified DC House system block diagram.
In this paper, a project whose goal is to design the EMS for the DC House in conjunction with the bi-directional DC-DC converter to improve both efficiency and cost-effectiveness is presented. The system itself will have the same overall functionality as the previous iteration: to safely control the flow of electricity between the bus, the battery, and the DC house. There are several possible approaches to improve the overall design. First is to reduce the overall price of the design to better meet the humanitarian goals of the DC House Project. The second is to implement a see-through case of the converter to better allow the users to view the device and identify any areas of damage due to the high voltage and current. The LCD screen could also be improved to show additional information about the device that is more user friendly such as the overall efficiency of the EMS and the mode of operation.

II. DESIGN REQUIREMENTS

The bidirectional DC-DC converter will be used in the DC house battery management system. This design will be focusing on improving efficiency while keeping the price low. The main connections for the converter are the 48V bus that connects to both the DC house and the renewable source through the MISO. On the other side, it connects to a 12V bus that connects to the Battery System. There are also several connections from different sensors that connect to the microcontroller which controls the flow of the power, this includes a battery change sensor and a signal from the MISO that tells us the available power that is being generated. Additionally, since the converter deals with relatively high voltages, a durable enclosure will be designed for the safety of the user.

The overall system design is shown in Fig. 2. The DC House load will vary based on the power needs within the house. If the renewable energy source provides the necessary power, the EMS system will send the power directly to the load. If the bus does not provide enough power, the Bi-Directional DC-DC converter will be connected, and the battery will provide the necessary power. If the Bus provides more power than is needed by the DC house load, the excess power will charge the battery. Based on this top-level design, more precise design choices can be made.

The state of the converter will be selected through the use of a microcontroller based on the State of Charge of the battery, the load demand, and the power provided from the MISO. The SOC chip is connected to a microcontroller to process the voltage, current, and temperature of the battery. By comparing these values with the voltage and current of the bus, the microcontroller will change the mode of the converter to meet the needs of the house. While the converter has built in sensing to switch between step-down (Buck mode) from 48V to 12V and step-up (Boost mode) from 12V-48V, the microcontroller will be used to switch between Buck and Boost mode so as to protect against overcharging the battery. The microcontroller will also be connected to an LCD screen to display the charge level of the battery, the current mode of operation, and the temperature of the system.

Table 1 provides a summary of the engineering specifications as well as general product design specifications and their justifications.

III. SYSTEM DESIGN

The design of the DC House Energy Management System (EMS) implements a single bi-directional converter. To improve the system, a more recent and updated controller was selected to improve efficiency and reduce cost. A new state of charge IC was also selected that has similar capabilities to the previous iteration of the project but in a smaller form factor. Fig. 3 shows a more detailed view of the two designed subsystems working together.

For the bi-directional DC-DC converter, the LTC8228 controller is selected due to its bi-directional buck and boost capabilities, wide input-output voltage range and over current protection. The switching frequency is set to be 249kHz by connecting a 38.3kΩ resistor from the RT pin to the ground. The inductor value is calculated using (1) based on a 30% maximum inductor current ripple. The same inductor is used in the power path in both buck and boost modes. Note for the following calculations the buck input voltage is referred to V1 = 48V and the boost input voltage is referred to V2 = 12V:

\[
L = \frac{V_2(V_1 - V_2)}{f_{SW}A_{loss}V_1^2} = \frac{12(48-12)}{249\times3.85\times48} = 9.38\mu H
\]

TABLE I. DC HOUSE EMS REQUIREMENTS AND SPECIFICATIONS

<table>
<thead>
<tr>
<th>Engineering Specifications</th>
<th>Justification</th>
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<tbody>
<tr>
<td>The design should have a single converter for the forward and backward conversions</td>
<td>The primary goal of this project is to have bi-directionality implemented</td>
</tr>
<tr>
<td>Total Power bank of 100Ah with a 12V battery</td>
<td>Must be able to sustain the house for at least 12 hours without being recharged.</td>
</tr>
<tr>
<td>DC Conversion efficiency of &gt; 90%</td>
<td>The previous iteration of this project peaked at roughly 88% efficiency; a 2% increase would be a notable markup.</td>
</tr>
<tr>
<td>Line and Load Regulation &lt; 5%</td>
<td>Low line and load regulations allow for a more robust and reliable system.</td>
</tr>
<tr>
<td>The system will change modes in real time to meet the needs of the load</td>
<td>Energy is wasted if the converter does not switch to the proper mode as quickly as possible, reducing efficiency.</td>
</tr>
<tr>
<td>DC-DC converter will convert between 12V and 48V and vice versa.</td>
<td>The bus and load run on 48V while the battery runs on 12V.</td>
</tr>
<tr>
<td>The total cost of the system should be &lt; $200</td>
<td>This is based on the previous project’s bill of materials for their final design.</td>
</tr>
<tr>
<td>The system will be in a weather-resistant enclosure</td>
<td>This will protect the system from damage from environmental effects.</td>
</tr>
<tr>
<td>An LCD screen will be used to show the current state of the converter</td>
<td>This allows the customer to know the current charge and mode of the converter.</td>
</tr>
<tr>
<td>The controller will have overcharge and temperature protection.</td>
<td>Overcharging or overheating can damage the battery bank, rendering it useless.</td>
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</table>
The Bias pin and Enable pin must have at least 8V so that the controller turns on and stays on. Two Schottky diodes, D2 and D3, are connected from V1 and V2 to these pins to ensure that these pins are set high in both Buck and Boost modes.

The Rsense for the battery sensing IC LTC2943 is selected based on the equation $Rsense < 50mV/Imax$ where $Imax$ is the maximum current from the battery. This gives $Rsense < 5.5mΩ$. Three 2kΩ resistors are placed between the ALCC, SDA, and SCL pins and a 3.3V pin on the Linduino One to limit the current. A 1µF capacitor is connected from the Sense+ pin to the ground as directed by the datasheet. The Linduino DC2026C is the selected microcontroller as it is the suggested microcontroller for use with the LTC2943.

IV. SIMULATION RESULTS

The software LTSpice is chosen to simulate this project. The main reason why LTSpice was chosen, rather than the other circuit simulators, is because both LT8228 and the battery sensing IC LTC2943 are manufactured by Analog Devices, the same company behind the software LTSpice. Additionally, LTSpice is chosen due to it being free meaning it was easily accessible to us and to anyone who might want to build on or confirm results at a later time.

In order to determine the operating efficiency of the buck and boost mode outputs, a resistive load was placed at the output to achieve specific output currents. Fig. 5 shows the Buck mode setup with a DC source input. When testing the Boost mode efficiency, the resistive load is placed at V1 and the Voltage source is placed at V2. In both modes, the load was stepped for 10% to 100% of the expected full load in iterations of 10% to compare the efficiency at each interval. The converter will be working under various loads in order to supplement the power provided to the DC House through the DC Bus. A voltage range of approximately ±5% was used for the input voltage in buck and boost modes to calculate the line regulation of the converter. Using the 10% and 90% load values, the load regulation was calculated.

In buck mode, as shown in Fig. 6 – Fig. 8, the input voltage is 48V and the output voltage is 12V. The expected output current is 8A and the input current is 2A at full load. These values would step down by 0.8A and 0.2A respectively as the load steps down 10%. At full load, the efficiency is 86% which is lower than the expected 94% from the datasheet. However, when compared to simulation data provided with the LT8228, our efficiency more closely matches up to the expected 87%. Part of this discrepancy is likely due to this design being for much lower power applications than the peak efficiency designs are. More specifically, this design is for an 8A output current compared to the 40A design that the chip allows for. The lower current also requires a lower current limit which increases the size of the Rsns sensing resistors. The datasheet recommends using a smaller Rsns value to achieve the highest efficiency.

The output voltage in buck mode at full load is found to have an average value of 11.9 V with about 0.045% percent ripple. Ideally, the output voltage should have no voltage ripple as it should be a DC voltage. A ripple of 0.045% is a negligible amount which is ideal for this design.

The average inductor current in buck mode is found to be 7.096A with a current ripple of about 2.46A, which is about 34% of the average right in line with the 35% ripple that was calculated. From the critical waveforms as shown in Fig. 8, it
becomes evident that M2 is acting as the main switch in this configuration, and M3 is acting as the synchronous switch. It is seen that the synchronous diode stays on for the majority of the time which is as expected for a buck converter with large input-output voltage decrease.

In boost mode, as seen in Fig. 9 – Fig. 11, the input voltage is 12V and the output voltage is 48V. Assuming ideal operation with no loss, the expected output current is 2A and the input current is 8A at full load. These values would step down by 0.2A and 0.8A respectively as the load steps down 10%. At full load, the efficiency is 84%, which is lower compared to the expected 93% from the datasheet. However, the simulation data provided in LTspice gives a lower efficiency of around 88% which more closely matches the measured efficiency. Similar to the buck mode, the lower power design requires a lower current limit to ensure a safe converter. The current limit has a large impact on efficiency as it increases the Rsns resistor values which in turn increases the value of many other resistors resulting in a greater power loss.

The output voltage in boost mode at full load is found to have an average value of 47.456V with a ripple of about 0.018% percent. Ideally, the output voltage should have no voltage ripple as it should be a DC voltage. A ripple of 0.018% is a negligible amount which is ideal for this design.
The average inductor current in boost mode is found to be 9.2A with a current ripple of about 2.25A which is about 24% of the average current which is under the 35% ripple accounted for which is a good thing. From the critical waveforms, it becomes evident that M3 is acting as the main switch in this configuration, and M2 is acting as the synchronous switch which is the opposite of what we found in the buck mode. It is seen that the synchronous diode stays on for the majority of the time which is as expected for a boost converter with large input-output voltage rise.

To calculate line regulation, a full load is used, and the input voltage was adjusted by ±5% from the nominal values for buck and boost modes. In buck mode, the input was tested at 45V, 48V, and 51V while in boost mode it was tested at 11.5V, 12V, and 12.5V. Table 2 shows the output voltages measured at each input voltage. Line regulation is calculated using the following equation:

\[
\text{LineRegulation} = \frac{V_{\text{out(high)}} - V_{\text{out(low)}}}{V_{\text{out(nom)}}} \times 100\% \quad (4)
\]

For buck mode, line regulation was 0.25%, and for boost mode line regulation was 0.13%. Generally, buck converters will have a low line regulation and boost converters will have higher line regulations. This converter has a low line regulation for both meaning that changes in the input voltage will have a very low effect on the output voltage. Both are well below the 2% regulation mark.

In order to calculate the load regulation, the output voltage was measured at the 10% and 90% loads in both buck and boost mode. This was done using resistive loads of 1.667Ω and 7.5Ω for buck mode, while for boost mode resistor values used were 24Ω and 120Ω. Load regulation is then calculated by the following equation:

\[
\text{LoadRegulation} = \frac{V_{\text{out(low)}} - V_{\text{out(high)}}}{V_{\text{out(high)}}} \times 100\% \quad (5)
\]

As seen in Table 3, for buck mode, the load regulation was 1.55% and for boost mode it was 0.147%. Low load regulation is ideal as it means that the output voltage does not react to changes in the load current. Generally, buck converters have poor load regulation while boost converters will normally have good load regulation. This is highlighted as the load regulation for the boost mode is roughly 10x smaller than buck mode. Both are below the 2% benchmark which is ideal.

V. CONCLUSIONS

This paper presents the design of an Energy Management System (EMS) for the DC House project to interface with the MISO converter. To achieve this, an improved PCB design was conducted to place both the converter IC and the SoC IC on the same board rather than on two separate boards; thus, reducing the overall size and price of the EMS system. The previous iteration of this system used a demo board, which made up a big portion of the total cost coming in at $370.00; however, this design would reduce the overall price significantly, costing less than $100 for parts and the printing of the circuit board. The simulation results of the DC-DC converter showed efficiency of 86% and 84% at full load in buck mode and boost mode, respectively. The efficiency remained fairly constant around 87% in buck mode and 85% in boost mode at lower loads. This converter will run more efficiently during daytime and evening hours where less power will need to be provided from the battery but worse during the night where all the power will need to come from the battery.

<table>
<thead>
<tr>
<th>Buck</th>
<th>Vin [V]</th>
<th>Vout [V]</th>
<th>Boost</th>
<th>Vin [V]</th>
<th>Vout [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vlow</td>
<td>45</td>
<td>11.91</td>
<td>Vlow</td>
<td>11.5</td>
<td>47.394</td>
</tr>
<tr>
<td>Vhigh</td>
<td>51</td>
<td>11.94</td>
<td>Vhigh</td>
<td>47.456</td>
<td></td>
</tr>
<tr>
<td>Vnom</td>
<td>48</td>
<td>11.9</td>
<td>Vnom</td>
<td>12</td>
<td>47.45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load</th>
<th>Vout [V]</th>
<th>Boost</th>
<th>Load</th>
<th>Vout [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>12.16</td>
<td>Low</td>
<td>10%</td>
<td>47.53</td>
</tr>
<tr>
<td>High</td>
<td>11.948</td>
<td>High</td>
<td>90%</td>
<td>47.45</td>
</tr>
</tbody>
</table>

One of the issues noticed while testing the current controller is that it functions most efficiently at loads higher than those required by the DC House. If in the future an alternative controller is desired, we recommend selecting one controller that operates well at relatively low loads. The LT8708 controller from Analog Devices according to its datasheet should reach 90% efficiency at a load of just 0.3A. Another controller with desired specifications is the LMS5170. The controller also promotes high efficiency at low loads, and it is specifically made for a 12V-48V application.

REFERENCES

Senior Project Report, Cal Poly State University, 2017.