DESIGN OF PORTABLE DC LIGHT BULB FOR THE DC HOUSE PROJECT

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By

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ABSTRACT

Design of Portable DC Light Bulb for the DC House Project

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This thesis focuses on the design and implementation of the Portable DC Light Bulb system for Cal Poly San Luis Obispo's DC House Project. The DC Portable Light Bulb highlights the NiMH battery charging circuit, buck converter, and boost converter. The system is intended as a flashlight adaptor placed in between the dimmable DC light bulb and its screw base. The adaptor adds a portability feature to the DC light bulb to provide lighting wherever the user pleases. The Portable DC Light Bulb system is designed to operate with an input range of 24V-60V and regulate an output voltage of 34V for the DC light bulb. Computer simulations, calculations, and hardware results verifies the proposed Portable DC Light Bulb system's design, function, and purpose.

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Chapter 1: Introduction

1.1 The DC House Project

The DC House Project is a student based project that highlights DC power generation and applications through multiple students' senior projects and Master's theses. The project's main purpose is to design and build an energy independent house that utilizes only direct current (DC) produced by generators. These generators use renewable energies converted from photovoltaic, wind, hydro, and human power. The DC power produced by these generators can be connected with minimal conversions to household appliances and other electrical devices. This DC connection reduces the overall power loss which increases the efficiency of the electrical system. The DC house is, therefore, self-sustaining and will be very much beneficial to communities that are inaccessible by the utility grid.

The DC house project was broken down into phases. Phase 1 included the initial design and modeling of the complete electrical system along with the power generation. Power generation and generator systems were analyzed and implemented to provide the main sources of the DC house. Renewable energy technologies were used such as solar panels, portable hydro-generators, wind turbines, as well as bicycle power for a more consistent source of energy. Phase 1 was completed in June of 2011.

Phase 2 focused on the DC house construction and the house's essential components. These components include the DC wall outlets, DC light bulbs, DC cell phone chargers, and other DC appliances. This phase provided the basic features of the DC house. Phase 2 was concluded in June of 2012.

Phase 3 is the most recent and on-going phase of the DC house project. It plans to improve past designs and features that will further push the value of the project. Improvements

are done to certain converters and concepts are expanding beyond its limits. A complete, physical DC house prototype is set to be built within this phase. Further phases will involve design optimization as well as field implementations of the DC house around the globe.

Chapter 2: Background

2.1 Motivation

Electricity is a luxury that people tend to take for granted. Not many even realize where the electrical energy comes from and how it is made. Today, our planet is troubled with depleting natural resources, such as fossil fuels, that act as the main source of energy in our lives. Because of this, we begin to turn towards renewable energy as better and more abundant sources of power.

The DC house project aims to assist communities that do not have access to electricity and power grids. To do so, the DC house project utilizes renewable energy to produce DC power. Usually, DC power is inverted into AC power to combine with company generators to power homes, wall outlets, and lighting systems. However, these conversions tend to present power losses which eventually affect the efficiency of the system. Most lighting systems and bulbs operate when electrons flow through the electric device and most are compatible with alternating current (AC) [1]. AC voltages alternate at a frequency of 50-60 Hz, depending on the country's generators. At these frequencies, the human eye cannot detect the fast changing direction of the electrons and view the light as continuous [2]. From this, we can conclude that using DC power is more efficient because the AC inversion process is skipped while providing the same functionality and results. Thus, the DC house project presents a clean solution to lesser class communities. Figure 2-1 is a simple block diagram of the DC house system that illustrates the DC power generation and distribution. Renewable energy devices transform resources, such as hydro, wind, and solar, into DC power by means of DC-DC converters. Each of those output are tied into a MISO (multiple input, single output) converter to produce the DC house bus line

at a nominal 48V. From the bus, many DC loads and DC applications are connected to create a complete, self-sustaining home [3].

Figure 2-1: Block Diagram of the DC House electrical System [3]

Furthermore, these communities do not have public lighting systems such as street lights or light posts. The DC house project offers another possible solution through its renewable electrical system. Flashlights can be used as a temporary form of outdoor lighting system for night time applications. Moreover, the DC LED light bulb can be used as the flashlight's bulb with the implementation of batteries as the portable source. This added feature further expands the convenience and ingenuity of the DC house.

2.2 DC Light Bulb

Since 1800, the invention of the light bulb has progressed through the works of many scientists and inventors. Humphry Davy was the first to develop the first electric light, known as the "electric arc lamp", by connecting a carbon filament to an electric battery. Davy discovered that the piece of carbon glowed enough to produce light when electricity was applied to it [4]. In 1860, Joseph Wilson Swan thought to enclose the lamp in a glass casing to allow the filament to

last longer. In 1877, Charles Francis Brush began to utilize the electric arcs in public areas as street lamps, stores, and other buildings [5]. Eventually, Thomas Edison was able to improve the electric arc lamp and produce the first incandescent light bulb in October 1878, shown in Figure 2-2. Edison continued to search for improvements and designed an electric lamp that could last for 1200 hours by November 1879. He accomplished this using a coiled carbonized bamboo filament and platina contact wires. Overall, the incandescent light bulb revolutionized the world by providing light and proving the importance and benefits of electricity.

Figure 2-2: Thomas Edison's original incandescent lamp [4]

Since then, the incandescent lamp has transformed into a better structured and more efficient light bulbs. Typically, a thin tungsten filament is incased by a glass mount filled with argon, or a type of inert gas. The incandescent light bulb uses the same concept of heating up the filament with electricity to result in light. Figure 2-3 illustrates the anatomy of an incandescent light bulb [6]. However, the energy provided by the electric source is not completely converted into light. Only about 5%-10% of the electrical energy is converted into visible light. The other

90%-95% becomes heat and is usually not the primary purpose of the light bulb [7]. Some advantages of the conventional incandescent light bulbs direct towards cost and ease of production.

Figure 2-3: Anatomy of an Incandescent Light Bulb [6]

Aside from the incandescent light bulb, there are various other types of bulbs such as halogen bulbs, compact fluorescent lamps (CFLs), and light emitting diodes (LEDs). Halogen bulbs are very identical to incandescent light bulbs but contain halogen gas, such as iodine or bromine, to react with the tungsten filament for a higher luminous efficiency [8]. These light bulbs are smaller in size and slightly better in efficiency than incandescent light bulbs. However,

halogen lamps produce heat at higher temperatures and cost more [9]. Compact fluorescent lamps are even more energy efficient and they produce light with a slightly different method. Instead of heating a tungsten filament, CFLs produce light by applying electricity in a coated, glass tube of fluorescent gas. Through this process, less heat is produced and about 75%-80% of the electrical energy is converted into light energy [10]. Despite their higher cost, fluorescent lamps last longer and are greatly more efficient than incandescent or halogen lamps. However, CFLs include the presence of mercury, a very dangerous element that can negatively affect a person's health [11].

Lastly, light emitting diodes, or LEDs, are the most efficient light source on the list. Its structure is that of a diode, a type of semiconductor that allows electrons to jump from the negative layer to the positive layer if the layers are connected to their respective ends of the circuit [12]. LEDs, however, emit light when the electrons of the semiconductor flow away from the negative layer and into the positive layer. Also, LEDs produce a brighter light for less energy than the other types of bulbs. Similar to compact fluorescent lamps, LEDs are considered as “cool” light sources because of how much less heat they produce [6]. Table 2-1 shown below demonstrates that LEDs produce more lumens for lower wattage than incandescent and fluorescent lamps [13]. For any amount of lumens, LEDs require the least amount of power compared to CFLs and incandescent lamps. LED light bulbs are more costly for each individual device, but pay off in the long run with the total cost considering the price of electricity and lifespan. One LED light bulb can cost up to \$100 each, but last as long as 50,000 hours or about 20 years before needing to be replaced [14]. Similar to CFLs, LEDs will operate at around 80% efficiency but will consume less power overall. In addition, the longer lifespan of the LED light bulb places it as the most energy and time efficient out of the various types of bulbs [15].

Table 2-1: Equivalent Wattages and Light Output of Incandescent, CFL, and LED bulbs

[13]

Light Output	LEDs	CFLs	Incandescents
Lumens	Watts	Watts	Watts
450	4 - 5	8 - 12	40
300 - 900	6 - 8	13 - 18	60
1100 - 1300	9 - 13	18 - 22	75 - 100
1600 - 1800	16 - 20	23 - 30	100
2600 - 2800	25 - 28	30 - 55	150

Unlike the other light bulbs, LEDs usually require extra electronics to drive the LED array safely and efficiently from AC power. The LED driver consists of a power converter and a feedback sensing circuit, similar to switched mode power supplies. The power conversion circuit allows the LED array to experience a regulated, consistent voltage regardless of the type and value of the input. This regulation is made possible by the sensing circuit and a control system to communicate with the power converter and its switching duty cycle. Proper design can also enable the LED array to dim, which lowers the system's power consumption. This circuitry plays a big part in the light bulb's high costs, but more importantly, its quality. Figure 2-4 very accurately depicts the structure of an LED light bulb [16].

Figure 2-4: Anatomy of the LED Light Bulb [16]

2.3 Available LED Light Bulbs

LED light bulbs are becoming more popular and are slowly replacing the lesser efficient light bulbs. House lights, street lights, and car headlights are only some of the long list of applications switching to LED bulbs [15]. Today, LED bulbs are readily available in most convenient stores or online. For example, Home Depot sells a variety of LED light bulb with identical screw bases as incandescent lamps or CFLs. They provide light bulbs of different wattages, brightness, colors, shapes, and brands for a price range of up to \$120 per bulb [17].

Figure 2-5 displays a \$24.97, 14 watt LED flood light bulb by Ecosmart available at Home

Depot. It is a soft white color bulb that can dim up to 800 lumens at about 57 lumens per watt. It is estimated to last up to 25,000 hours and is equivalent to a 75 watt incandescent light bulb [18].

Figure 2-5: Ecosmart 14-Watt LED Flood Light Bulb [18]

LED flashlights are also readily available in stores and are beginning to become more popular than typical flashlights. The reason lies within the overall efficiency, size, and performance of the LED flashlight. The advantages that come with LED flashlights are identical to the advantages of the LED light bulb: less energy converted into heat, more lumens for less power, and lifespan is dramatically larger than a regular flashlight. Because LEDs require less power, the system consumes less current. This allows batteries to last much longer and, in turn, allows for smaller size batteries such as AA or AAA. Smaller batteries reduce the flashlight's physical weight and bulk while sustaining for longer periods of time.

Like most battery powered devices, some LED flashlights are rechargeable by means of a portable external charger. To charge the batteries, they are often condensed into a battery pack that is easily taken out of the battery and charged on the battery station, which utilizes an AC converter and wall outlets. For example, Figure 2-6 shows the package of the MAGLITE ML125

LED rechargeable flashlight system, complete with a NiMH battery pack and portable battery charger [19].

Figure 2-6: MAGLITE ML125 LED Rechargeable Flashlight System [19]

Other LED rechargeable flashlights use a charging dock instead of an external battery charger. Figure 2-7 displays the Pelican 8060 LED flashlight placed in the charging station. The charging dock eliminates the small step of extracting the battery from the flashlight to charge. Otherwise, it still requires an AC converter similar to the previous LED flashlight.

8060 LED IN
CHARGING DOCK

Figure 2-7: Pelican 8060 LED Rechargeable Flashlight System [20]

More specifically, there are a handful of plug in LED rechargeable flashlights available in common stores. The AC adapter is built in and the batteries are recharged while the flashlight is either on or off. Figure 2-8 shows a plug in LED rechargeable flashlight and its fold-out wall charger feature on the backside [21]. However, it is uncommon for these flashlights to operate at full power when charging and it becomes a night light instead of a household lamp. It would be very inconvenient to try to use a plug in rechargeable flashlight as a lamp because of its low intensity and poor room placement. These lamps are limited to wall outlets and lower heights.

Figure 2-8: Dorcy LED Rechargeable Flashlight [21]

2.4 DC House Project

The DC house project recently acquired a design of a DC light bulb by Kent Liang [22]. He designed a custom DC light bulb to operate with the optimal 48V DC house bus. The goal of the project was to maintain efficiency by choosing LED bulbs and keep the DC power throughout the system.

The light bulb consists of four LEDs that created the LED array and driven by a LED driver. The LED Driver is paired with a dimming circuit to control the brightness of the LED light bulb. Figure 2-9 illustrates a system level block diagram of Mr. Liang's DC Light Bulb. The system is broken up to three subsystems, each having its own purpose and share of complex circuitry.

Figure 2-9: Kent Liang's DC Light Bulb Block Diagram [22]

The dimming circuit contains the pulse width modulator (PWM) controller using LTC699-1 and two low dropout (LDO) regulators using LT3014. The LDO regulators are used to provide the necessary voltage to power the PWM controller chip. The regulators take from the main 48V input line to drop out to 5V and again to 1.22V. The PWM controller can be adjusted, by the dimmer, to output a certain voltage (PWM5V) to the LED driver. This voltage can adjust the intensity of the LED array through the LED driver.

The LED driver regulates a desired voltage to match the characteristics of the LED array. It contains its own power converter controlled by the PWM controller from the dimmer circuit. The driver can drive LEDs using a variety of DC-DC converter topologies such as Buck, Boost,

Buck-Boost, Sepic, or Flyback. For this project, the Buck topology was selected because the LED array requires 12.6V which is stepped down from 48V.

Lastly, the led array holds four CREE XPG LEDs in series. The LEDs were chosen based on the current rating at 1.5A and forward voltage of 3.25V. The selected LEDs offer a luminous efficacy of 110 lumens per watt.

The DC light bulb was designed and simulated for an input range of 24V to 72V, but was only tested between 33V to 63V for safety reasons. The completed DC LED light bulb consumed a total of 13.44 watts and 85.631% efficiency at full load.

2.5 Thesis Objective

This thesis proposes to expand on the functionality of the previously designed DC House light bulb. In particular, a flashlight adapter will be connected between the 48V DC house bus and the LED light bulb. This additional feature is important for the DC House application especially in remote villages where having a flashlight will help people travel during night time. This thesis therefore focuses around the design, implementation, and testing of the Portable DC Light Bulb system for the DC house project. Batteries are added to the initial DC light bulb to add the feature of portability as a flashlight. While the device is connected as a DC light bulb, the batteries are charged using the DC power produced by the house. This lighting system highlights the buck DC-DC converter design, charging circuit design, and the boost DC-DC converter design. Hardware implementation of the Portable DC Light Bulb will be conducted and tests will be performed to verify its operation, functionality, and performance.

Chapter 3: Design Requirements

3.1 Battery Selection

The two most common non-rechargeable batteries are: Zinc and alkaline. Zinc batteries use electrodes of zinc and carbon consistency and an acidic paste as the electrolyte. On the other hand, alkaline batteries use zinc and manganese-oxide electrodes with alkaline paste [23]. Zinc-carbon and zinc-chloride batteries can usually be found in AA, C, and D sizes and were one of the first popular types of non-rechargeable batteries. Around 1970, alkaline batteries began to overtake zinc batteries because of cost and performance. Alkaline batteries have higher capacities, lower costs, and longer battery life, making them convenient and eventually the most common household battery [24].

Advances in technology result from smaller electrical components and larger quantities within a device. More electrical components demand more power which result in demands for higher battery capacities [25]. Rechargeable batteries help fulfill this criteria by allowing the battery to be charged more than once and providing the convenience of not having to replace depleted, non-rechargeable batteries.

While non-rechargeable batteries are referred to as primary cells, rechargeable batteries are also known as secondary cells. Both types of batteries transform energy using the same chemical reaction. However, secondary cells are able to reverse the reaction and “recharge” the battery. To reverse this process, an external source of electrical energy pushes the electrons to flow from the positive to the negative electrode. As a result, the battery becomes more charged and ready to discharge once again [26].

Like primary cells, rechargeable batteries present a variety of chemistries as well. The most common chemistries are lead-acid, nickel, and lithium-ion. Lead-acid batteries use lead or

lead-oxide electrodes and an electrolyte made of a strong acidic material. They are one of the oldest types of rechargeable batteries and are typically used as car batteries [23].

Nickel-cadmium, or NiCd, batteries have nickel-hydroxide and cadmium electrodes and a potassium hydroxide electrolyte [23]. They became very popular household batteries when it became available to the public. However, a disadvantage with NiCd batteries is called the memory effect. The battery's capacity and lifespan begin to decrease with the amount of times the battery is recharged [26]. Another big disadvantage to NiCd batteries are its negative effects on the environment. They contain toxic metals that are dangerous to the environment if disposing is not handled properly. NiCd batteries are better suited for heavy duty applications that require a high discharge rate. Identically, NiCd batteries also work best with high charging rates, or fast charging, and pulse charging rather than a straight DC charge. Constantly keeping a NiCd battery in a charger will gradually affect its capacity and overall performance [27]. Although NiCd batteries are cheaper, NiMH batteries prove to be better in quality. Nickel-metal hydride, or NiMH, has a nickel hydroxide positive electrode and a hydrogen negative electrode. Like the NiCd battery, NiMH has a potassium hydroxide electrolyte. This configuration creates a higher energy density than NiCd and makes the NiMH battery an ideal choice for high power and active applications [28]. However, NiMH batteries have a shorter shelf life and aren't suitable for high discharge applications like NiCd batteries. To compensate for these disadvantages, NiMH batteries are lighter in weight and do not contain toxic materials found in NiCd batteries [24].

Lithium ion batteries offer the best performance out of all of the rechargeable batteries. They are very versatile because of their higher energy density, long life, and very light weight. In addition, they do not experience the memory effect like the nickel based batteries. Lithium ion batteries are typically used in high powered electronic devices such as laptops, cell phones, and

cameras. However, Lithium ion batteries cost much more than the other types of secondary cells. They also require more complex charge circuit to properly recharge the battery and prevent overcharging [26].

For the DC LED rechargeable flashlight, the NiMH battery was chosen as the battery chemistry. Considering the target audience of the DC house project, battery availability and cost proved the NiMH battery to be the most suitable choice. In the emergency that a rechargeable battery needs to be replaced, it would be cheaper and more common to obtain a nickel based battery than a lithium ion battery. This also benefits the charging stage by requiring a less complex circuit. Between the two nickel based batteries, NiMH batteries are safer and are able to handle this active application without affecting performance and battery life. As stated in the previous sections, NiMH batteries are more environmental friendly and have higher capacities than NiCd.

AA, AAA, C, and D are the most common household batteries sizes in the market. Table 3-1 compares the four batteries and its NiMH features [29]. C and D batteries have significantly larger capacities than the AA and AAA batteries. However, AA and AAA batteries are more popular because of their smaller size and weight compared to the bulkier, heavier C and D batteries. Between AA and AAA batteries, AA batteries are slightly larger in diameter, but have higher capacities than AAA batteries making it a suitable choice for the DC LED rechargeable flashlight. Thus, the battery size was chosen to be AA because of its commonality and capacity. Figure 3-1 illustrates a pair of AA NiMH 2500mAh rechargeable battery by Energizer available at Walmart for \$13.00 [30].

Table 3-1: Common Batteries Comparison Chart

Battery Size	Typical Capacity (mAh)	Nominal Voltage (V)	Dimensions (Len. X Dia.) (mm)
AAA	800-1,000 (NiMH)	1.2 (NiMH)	44.5 x 10.5
AA	1,700-2,900 (NiMH)	1.2 (NiMH)	50.5 x 13.5
C	4,500-6,000 (NiMH)	1.2 (NiMH)	50 x 26.2
D	9,000-11,500 (NiMH)	1.2 (NiMH)	61.5 x 34.2

Figure 3-1: Energizer AA NiMH 2500mAh Rechargeable Battery [30]

Battery configurations also play a big part in optimizing the performance of the battery pack. It is not advised to mix batteries of different size or capacities to avoid charging issues. When batteries are connected in series, the cell voltages are added while the capacities remain the same. For example, four 1.2V 2,000mAh batteries in series will produce a 4.8V 2,000mAh battery pack. This increase in voltage will allow less discharge current for the same power. Therefore, the battery pack retains its charge for a longer period of time. Figure 3-2 displays two 6V 10Ah batteries in series and the resulting voltage and capacity. On the other hand, parallel configurations will maintain the cell voltage, but add the battery capacities. For example, four 1.2V 2,000mAh batteries in parallel will produce a 1.2V 8,000mAh battery pack. Although the

pack sits at a low voltage, it now has a much higher capacity allowing for even higher discharge currents per hour. However, the parallel configuration may cause charging and discharging issues because a slight difference in cell voltages can cause the batteries to recharge each other [31].

Figure 3-2: Example of Batteries in Series Configuration [31]

The number of batteries in series was found using the output power required by the DC light bulb. As stated in the previous chapter, the DC light bulb consumed 13.44W at full load (dimmer at 100%). The required output current, or discharge current, can be calculated using the power equation and the battery pack voltage.

$$I_{dis} = \frac{P_{out}}{V_{batt}} \quad (3.1)$$

The output power of the battery, or the required input power of the DC light bulb, can be decreased to 0 as the DC light bulb's dimmer decreases to 0% duty cycle and the DC light bulb consumes less and less power. However, we will consider the output power at full load and up to 16W for worst case situations. The battery voltage, V_{batt} , depends on the number of batteries in series and will be calculated for up to 6 cells. Next, the discharge time of the battery is calculated for both best and worst typical capacities using the equation shown below. Battery capacity units are in mAh while discharge currents are in amps.

$$\text{discharge time in minutes} = \frac{(\text{battery capacity}) * 60}{(I_{dis} * 1000)} \quad (3.2)$$

While stores usually sell AA NiMH batteries at 2,300mAh and 2,700mAh, a larger range of capacities will be used to provide a better insight in battery performances. Worst case capacity was set for 800mAh while the best case capacity was set for 2,800mAh. Table 3-2 shows the discharging times for up to 6 cells in series. Note each battery cell is set to the nominal 1.2V and can be as best as 1.5V at a completely charged state.

Table 3-2: Discharge Times, (a) 1 Cell, (b) 2 Cells in Series, (c) 4 Cells in Series, (d) 6 Cells in Series

Po (W)	Io (A)	Worst Case Time (minutes)	Best Case Time (minutes)
12	10.00	4.80	16.80
13	10.83	4.43	15.51
14	11.67	4.11	14.40
15	12.50	3.84	13.44
16	13.33	3.60	12.60

(a) 1 Cell; $V_{batt} = 1.2V$

Po (W)	Io (A)	Worst Case Time (minutes)	Best Case Time (minutes)
12	5.00	9.60	33.60
13	5.42	8.86	31.02
14	5.83	8.23	28.80
15	6.25	7.68	26.88
16	6.67	7.20	25.20

(b) 2 Cells; $V_{batt} = 2.4V$

Po (W)	Io (A)	Worst Case Time (minutes)	Best Case Time (minutes)
12	2.50	19.20	67.20
13	2.71	17.72	62.03
14	2.92	16.46	57.60
15	3.13	15.36	53.76
16	3.33	14.40	50.40

(c) 4 Cells; $V_{batt} = 4.8V$

P_o (W)	I_o (A)	Worst Case Time (minutes)	Best Case Time (minutes)
12	1.67	28.80	100.80
13	1.81	26.58	93.05
14	1.94	24.69	86.40
15	2.08	23.04	80.64
16	2.22	21.60	75.60

(d) 6 Cells; $V_{\text{batt}} = 7.2 \text{ V}$

It can be observed that more battery cells in series decreases the required current, I_o , which increases the discharge time. This allows the battery to supply the load for a longer period of time, a desirable trait for any portable device. It is also observed that higher capacities (best case at 2,800 mAh) provide longer discharge times than lower capacities (worst case at 800 mAh) at the same power. Ideally, fewer cells in series is preferred for size and weight reasons. However, higher capacities are favorable, pointing towards 4-6 cells in series. More than 6 cells in series was also considered, but will increase the overall weight and bulk of the design. As a result, 6 AA NiMH cells in series was chosen as the most suitable amount of batteries for the DC LED rechargeable flashlight. Despite the weight accompanied by 6 battery cells, it overtakes 4 battery cells by about 25-35 minutes. Table 3-3 displays a more complete discharging time chart over a larger power range. Additionally, 6 battery cells in series can last around 1 hour for an output power as high as 18W.

Table 3-3: Discharge Time for 6 Cells in Series and Nominal Battery Voltage

Po (W)	Io (A)	Worst Case Time (minutes)	Best Case Time (minutes)
1	0.14	345.60	1209.60
2	0.28	172.80	604.80
3	0.42	115.20	403.20
4	0.56	86.40	302.40
5	0.69	69.12	241.92
6	0.83	57.60	201.60
7	0.97	49.37	172.80
8	1.11	43.20	151.20
9	1.25	38.40	134.40
10	1.39	34.56	120.96
11	1.53	31.42	109.96
12	1.67	28.80	100.80
13	1.81	26.58	93.05
14	1.94	24.69	86.40
15	2.08	23.04	80.64
16	2.22	21.60	75.60
17	2.36	20.33	71.15
18	2.50	19.20	67.20

3.2 Battery Charger Selection

Overcharging can permanently damage the battery cells, reduce capacity, or cause battery failure. NiMH batteries require proper charge terminations to prevent overcharging the battery pack. Like most types of battery chemistries, NiMH must only be charged with a NiMH charger to further prevent overcharging. NiMH batteries charge best with rapid chargers, or fast chargers, for a fixed time and then lowered to a trickle charge. Trickle charging is a charging method that continues charging the battery at a low charge current, typically 250mA or less [32]. Trickle charging, by itself, is highly recommended in charging NiMH batteries. However, a low charge current can take up to 10-20 hours to fully charge.

The three types of NiMH charger charge terminations include timer, $-\Delta V$, and $\Delta T/\Delta t$. The timer charge termination stops charging after a designed, fixed time limit. The timer termination is especially important for fast chargers with high charge rates and charge currents. The $-\Delta V$ charge termination monitors the change of battery cell voltage across a period of time. Once the battery is approaching its fully charged state, the ΔV of the battery cells will increase and suddenly rise drastically. This sharp slope triggers the charger to stop and, once again, avoid overcharging. Lastly, the $\Delta T/\Delta t$ charge termination operates very similar to the $-\Delta V$ charge termination. Instead, it monitors the change in temperature and detects sudden temperature rises to turn off the charger. When the cells are charging regularly, the electrical energy is reversed into chemical energy. Once it approaches its fully charged state, the electrical energy begins to convert into heat instead. A thermistor, or thermal resistor, is commonly used to monitor the physical temperature of the battery pack and engage charge termination [33].

The LTC4011, High Efficiency Standalone Nickel Battery Charger, was chosen as the DC LED rechargeable flashlight's charging stage. It can be set to charge either NiCd or NiMH batteries, up to as many as 16 battery cells. It exhibits all three important NiMH charge terminations built-in to optimize protection from overcharging. Figure 3-3 clearly demonstrates the changes in voltage and temperature of a charging cell. The LTC4011 switches from a fast charge rate into a top off charge, or trickle charge, after it experiences a steep change in either voltage or temperature. Furthermore, an integrated power path control network is readily available for the chip. PowerPath, a method designed by Linear Technology, provides power to the system load at all times, either from the input DC source or the battery pack. It also prevents any interruptions, by the system load, to the charge terminations. Additional advantages to this charger chip include programmable charge current, charge operating state outputs, and a

synchronous step-down design for high efficiency. These design features prove that the LTC4011 is safe, convenient, and suitable for the DC LED rechargeable flashlight [34].

Figure 3-3: LTC4011 Charge Cycle and Cell Behaviors [34]

3.3 DC-DC Converter Selection

The LTC4011 requires a DC input voltage minimum for the charging system depending on the number of cells in series. The datasheet provides the equation below, where n is the number of cells in series.

$$DC_{in(min)} = [n * (2V)] + 0.3V = [6 * (2V)] + 0.3V = 12.3V \quad (3.3)$$

For 6 AA NiMH battery cells in series, an input voltage of 12.3V is required to provide an adequate source for the charging system. The LTC4011 has an input voltage limit of 36V while the DC house operates at a nominal 48V. To compensate for this issue, a DC-DC buck converter prior to the charger is needed to step down the 48V DC house bus below the 36V input voltage limit. Furthermore, the LTC4011 typical performance characteristics show that the

charger exhibits better efficiency with lower DC input voltages. Thus, a buck output, and charger input voltage, was chosen to be 17V. 17V is a low enough voltage for better charger efficiency while meeting the requirements for up to 8 AA NiMH battery cells in series.

The LTC3891, Low I_Q , 60V Synchronous Step-Down Controller, was selected to fulfill the criteria as the buck converter in the system. It has a very wide input voltage range of 4V to 60V, a beneficial feature that would make the DC LED rechargeable flashlight more versatile. The LTC3891 can regulate an output voltage between 0.8V and 24V and hold estimated efficiencies up to 95% at lower loads. Another useful feature of the LTC3891 is its Burst Mode operation for light loads. Burst Mode Operation is a method designed by Linear Technology to force continuous conduction mode and better efficiency at low loads. Additional features include current sensing, programmable soft-start, and synchronous operation [35].

Kent Liang's DC light bulb was designed and simulated to operate at a minimum voltage of 24V, but was only tested down to 33V. In addition, the system load will run on the battery pack voltage if there isn't a DC input source present. The battery voltage may be as low as 7.2V for 6-1.2V cell batteries. Therefore, a DC-DC boost converter must be used to step up the charger output voltage to the minimum 33V input value for proper and safe operation with the DC light bulb. The boost was selected to output 34V to avoid operating at the bare minimum voltage.

The LTC3786, Low I_Q Synchronous Boost Controller, was selected to satisfy this requirement. It has an input voltage range of 4.5V to 38V, suitable for battery voltage as low as 7.2V and buck/charger output voltage as high as 17V. The LTC3786 has estimated efficiencies up to 97% for higher loads. Similar to the LTC3891 step-down controller, the LTC3786 includes Burst Mode operation, current sensing, programmable soft-start, and synchronous operation [36].

3.4 System Requirements

The Portable DC Light Bulb system adds a portability feature to the DC Light Bulb by means of the DC flashlight adaptor. The adaptor system consists of the buck converter, charging circuit, and boost converter selected in the previous sections.

The DC flashlight adaptor is required operate with a wide input voltage range, most specifically at 48V. It must be able to initiate charging operation and terminate automatically. Most importantly, it must be compatible with the existing DC House light bulb. The DC House light bulb was tested for an input range of 33V-63V. The DC flashlight adaptor must have an output voltage within the DC House light bulb's input range to ensure safe and proper operation. The DC House light bulb consumes 13.44W at full load [22]. The DC flashlight adaptor is required to transfer beyond 13.44W to supply the light bulb's power requirements.

The adaptor will be placed in between the DC House light bulb and its screw base. To be used as a flashlight, the system will be unscrewed and disconnected from the screw base. The system will then operate through the implemented batteries. Furthermore, the DC flashlight adaptor must handle the DC House light bulb's dimming feature.

The buck converter output voltage was required to fit within a range of voltages required by the charging circuit. The charging circuit needed a minimum voltage of 12.3V to properly charge 6 battery cells in series and 16.3V to charge 8 cells in case of expansion. The charging circuit also has a chip rating of 34V maximum input voltage. Thus, the buck converter output was selected as 17V. The load and line regulation and $\%V_{Opp}$ requirements were set at $\pm 2\%$ to ensure that the output ripple will neither reach nor exceed the given limits.

The DC light bulb was designed for an input range of 24V-72V. Therefore, the boost converter output was selected as 34V, a value within the required input range. The minimum

limit, 24V, is approximately -30% of 34V while the maximum limit, 72V, is about 112% of 24V. Thus, the load and line regulation and %V_{Opp} requirements were set at $\pm 5\%$ to ensure that the output ripple will neither reach nor exceed the given limits.

Lastly, the overall system efficiency design requirement was set at 80% for any case. To achieve this efficiency, the buck and boost converters each must operate at approximately 90%. This should provide 81% overall system efficiency because cascaded system efficiencies are multiplied. Table 3-4 summarizes the Portable DC Light Bulb system design requirements.

Table 3-4: Portable DC Light Bulb System Design Requirements

	Design	
	Buck	Boost
Line Regulation	2%	5%
Load Regulation	2%	5%
Efficiency	90%	90%
%V_{Opp}	2%	5%

Chapter 4: Design and Simulation Results

4.1 System Level Design

From a system level design, the Portable DC Light Bulb system includes a DC flashlight adaptor that fits in between the 48V DC input source and the DC light bulb. Figure 4-1 illustrates the level 1 block diagram of the Portable DC Light Bulb system.

Figure 4-1: Portable DC Light Bulb System Level 1 Block Diagram

The VIN input is connected to the 48V DC house bus. The VO output represents the output voltage of the DC flashlight adaptor that becomes the input voltage to the DC light bulb. The LIGHT output of the DC light bulb describes the lumination, or brightness, produced by the bulb. The ADJ input of the DC light bulb signifies the user feedback signal adjusted by the DC light bulb's dimmer circuit via slider. The ADJ input determines the intensity of the LIGHT output. Table 4-1 summarizes the Portable DC Light Bulb system level 1 block diagram's inputs and outputs along with their functionalities.

Table 4-1: Portable DC Light Bulb System Level 1 Functionalities

Subsystem Name	I/O	Signal Name	Functionality
DC Flashlight Adaptor	Input	VIN	Nominal 48V from DC house bus.
	Output	VO	Regulated output voltage of the boost converter powering the DC light bulb.
DC Light Bulb	Input	VO, ADJ	Regulated voltage supplied by the DC flashlight adaptor. ADJ is a user feedback signal via sliding potentiometer.
	Output	LIGHT	LED light lamination.

The DC flashlight adaptor can be further broken down into a level 2 block diagram. This adaptor adds the portability feature to the DC light bulb similar to that of a flashlight. The DC flashlight adaptor includes three main subsystems and the rechargeable battery pack as the portable energy source. The three main subsystems consist of the buck converter, charging circuit, and boost converter. Figure 4-2 displays the level 2 block diagram of the DC flashlight adaptor.

Figure 4-2: DC Flashlight Adaptor Level 2 Block Diagram

The buck converter circuit takes in the same VIN input from the level 1 block diagram. This circuit steps down 48V from the DC house bus to 17V at VBU, or VBUCK. VBU becomes

the regulated input of the charging circuit to charge the battery pack, V_{batt} , and supply power to the boost converter at V_{BO} , or V_{BOOST} . The boost converter steps up the voltage at V_{BO} to 34V at V_O to supply the required voltage of the DC light bulb. In the case that the system is not connected to the DC house the system operates in flashlight mode and utilizes the battery pack as the system source. V_{batt} represents the battery voltage which fluctuates depending on its charge. The charging circuit's powerpath control allows V_{BO} to switch between V_{BU} and V_{batt} depending on the presence V_{IN} . Table 4-2 summarizes the DC flashlight adaptor level 2 block diagram's inputs and outputs along with their functionalities.

Table 4-2: DC Flashlight Adaptor Level 2 Functionalities

Subsystem Name	I/O	Signal Name	Functionality
Buck Converter	Input	V_{IN}	Nominal 48V from DC house bus.
	Output	V_{BU}	Regulated 17V output voltage lowered to meet charging circuit requirements.
Charging Circuit	Input	V_{BU}	Regulated voltage supplied by the buck converter.
	Output	V_{BO} , V_{batt}	Either regulated voltage provided by V_{BU} with slight voltage drop or by battery voltage, V_{batt} .
Boost Converter	Input	V_{BO}	Voltage supplied from charger either from buck converter or batteries.
	Output	V_O	Regulated 34V output voltage boosted to meet DC light bulb requirements.

In the following sections, each circuit of the DC flashlight adaptor will be analyzed and presented in detail. For each circuit, component selection and sizing will be justified and the circuit will be proven through simulation using LTSpice. First, the boost converter will be analyzed, followed by the charging circuit, and then the buck converter.

4.2 Boost Converter Design

The DC flashlight adaptor depends on the power requirements of the DC light bulb. The light intensity and power requirement varies along with the PWM duty cycle via slide potentiometer. The input and output power of the DC light bulb was measured and observed to increase with the duty cycle. Table 4-3 displays the minimum and maximum power measurements as described in [22].

Table 4-3: DC Light Bulb Power Measurements [22]

Duty Cycle (%)	Light	Pin (W)	Po (W)
0.00	OFF	0.104	0.000
2.97	ON	0.512	0.247
95.52	ON	12.952	10.857
100.00	ON	13.456	11.519

The current drawn by the DC light bulb was calculated through the power equation using 34V, the regulated boost output voltage. The calculation for 100% dimmer PWM duty cycle is shown below.

$$I_{\text{req}} = \frac{P_o}{V_{\text{Boost}}} = \frac{13.456 \text{ W}}{34 \text{ V}} = 0.396 \text{ A} \quad (4.1)$$

For 2.97% dimmer PWM duty cycle, the required current, I_{req} , was calculated to be 15mA and 3mA for 0% dimmer PWM duty cycle. However, the required current for a load beyond 100% will be considered for worst case scenarios. For 15W, the required current was found to be 0.44A. The switching frequency of the synchronous regulator was set to 350 kHz by connecting the FREQ pin to the system ground.

The converter duty cycle can be determined through the boost transfer function shown in equation 4.2.

$$\text{Duty Cycle} = \frac{V_o - V_{\text{in}}}{V_o} \quad (4.2)$$

Because the boost converter has multiple possible input voltages, the duty cycle for the typical values will be calculated. Typical voltages include 7.2V and 9V to represent battery pack voltages at 1.2V and 1.5V per cell, respectively. When a DC input source is present, the boost may experience a voltage between 16V and 17V depending on the power path voltage drop. Table 4-4 shows the calculated duty cycles for each input voltage for 34V output voltage.

Table 4-4: Boost Duty Cycles for Various Input Voltages

Input Voltage (V)	Duty Cycle (%)
7.2	78.8
9	73.5
16	52.9
17	50.0

As stated above, the dimmable DC light bulb can require currents as low as 3mA. A boost I_O of 3mA can push an I_{Lmin} of as low as 6mA for 17V input or 14mA for 7.2V input. Very low inductor current minimums need higher inductances to reduce current ripple and avoid operating in DCM, or discontinuous conduction mode. To avoid DCM and a very large inductor size, the Burst Mode operation is selected on the LTC3786 by connecting the PLLIN/MODE pin to ground. Other modes include forced continuous mode and pulse-skipping mode, both which allows the inductor to operate at lighter loads. Figure 4-3 illustrates the comparison of inductor currents for each mode. However, LTC3786 typical performance characteristics show that Burst Mode operation is the most efficient.

Figure 4-3: Inductor Currents for LTC3786 Modes

Although the LTC3786 was set for Burst mode operation, the inductor was selected to handle loads as low as possible while considering the physical size of the inductor and its availability. For the boost converter, the output current is also the diode current and a fraction of the inductor current depending on duty cycle. As stated above, the required current for 15W is 0.44A. As a further buffer, I_{Omax} was set to 0.45A, giving up an I_{Lmax} of 2.125A for 78.8% duty cycle. The maximum inductor current can be used to calculate current ripple, minimum inductor current, inductor current peak, and inductance for a given percent ripple. These values were found for percent ripples between 5%-30% shown in Table 4-5. The calculated values provide inductor current characteristics for various inductances.

$$I_{Lmax} = \frac{I_{Omax}}{(1-D)} \quad (4.3)$$

$$\Delta I_L = (\% \text{ ripple}) * I_{Lmax} \quad (4.4)$$

$$I_{Lmin} = \frac{\Delta I_L}{2} \quad (4.5)$$

$$I_{Lpeak} = I_{Lmax} + \frac{\Delta I_L}{2} \quad (4.6)$$

$$L_C = \frac{V_{in}}{\Delta I_L * f_{sw}} \left(1 - \frac{V_{in}}{V_o}\right) \quad (4.7)$$

Table 4-5: Inductance and Current Characteristics for Boost Inductor Selection

% ripple	ΔI_L (A)	I_{Lmin} (A)	I_{Lpk} (A)	L_c (μH)
0.30	0.64	0.32	2.44	25
0.25	0.53	0.27	2.39	31
0.20	0.43	0.21	2.34	38
0.15	0.32	0.16	2.28	51
0.10	0.21	0.11	2.23	76
0.05	0.11	0.05	2.18	153

Given the range of inductances, 100 μH was selected as the most suitable value. Although a higher inductance is preferred, the inductor dimensions and availability were also considered. Table 4-6 shows the inductor current characteristics through back-calculation using the equations above.

Table 4-6: Inductor Current Characteristics for 100 μH

Inductance (μH)	100
ΔI_L (A)	0.162
% ripple	7.6%
I_{Lmin} (A)	0.081
I_{Lpk} (A)	2.21

The LTC3786 regulates the voltage by means of current sensing. Pins SENSE⁺ and SENSE⁻ were connected to a sense resistor placed right before the inductor. The sense resistance was determined using the equation provided in the datasheet and found to be 33m Ω , as shown below. The regulator has a maximum threshold $V_{sense(max)}$ set to 75mV. To improve the sensing, an RC filter was placed across the sense pins.

$$R_{sense} = \left(\frac{V_{sense(max)}}{I_{Lmax} + \frac{\Delta I_L}{2}} \right) = \left(\frac{0.075V}{2.21A} \right) = 0.033\Omega \quad (4.8)$$

The output voltage can be programmed using an external feedback resistor divider connected to the output node, V_{FB} pin, and GND. The resistor values were calculated using the equation, provided by the LTC3786 datasheet, shown below.

$$V_O = 34V = 1.2V \left(1 + \frac{R_B}{R_A}\right) \quad (4.9)$$

Resistor R_B was arbitrarily chosen as 97.6k Ω and R_A was calculated to be 3.57 k Ω using equation 4.9. R_B and R_A were designated as R_{10} and R_9 , respectively. Similarly, the RUN resistor divider can be calculated using equation 4.10 below. Forcing the RUN pin under 1.28V shuts the controller loop and the boost converter does not operate. The controller was programmed to halt operation at 6V, the worst case battery pack voltage. Note that the battery charge will be depleted before the battery pack voltage reaches 6V.

$$V_{RUN} = 6V = 1.28V \left(1 + \frac{R_B}{R_A}\right) \quad (4.10)$$

Resistor R_B was arbitrarily chosen as 100k Ω and R_A was calculated to be 27k Ω using equation 4.10. R_B and R_A were designated as R_{11} and R_{12} , respectively. The soft-start feature gradually increases the regulated output voltage over a fixed time, rather than rising suddenly. This allows smoother operation between the boost converter and the prior systems. The boost soft start is chosen to be around 26ms to permit enough time for the buck converter to regulate its voltage. Capacitor C_{SS} can be calculated using the equation below, provided by the datasheet. Capacitor C_{SS} was designated as C13.

$$C_{SS} = t_{SS} \left(\frac{10\mu A}{1.2V}\right) = (0.0264s) \left(\frac{10\mu A}{1.2V}\right) = 0.22\mu F \quad (4.11)$$

A Schottky diode, D4, was implemented across the main boost switch, M2, to reduce switching loss during dead time and increase efficiency.

The LTC3786 boost converter complete, final schematic is shown in Figure 4-4. LTSpice was used to simulate and evaluate the circuit. Ideally, the boost converter will operate at 17V with 0.396A load (13.456W).

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(a)

(b)

(c)

(d)

Figure 4-5: Boost Converter Waveforms for $V_{in} = 17V$ and $I_O = 0.44A$, (a) Output Voltage Ripple, (b) Inductor Current Ripple, (c) M1 Gate Voltage, (d) M2 Gate Voltage

Table 4-7: Efficiency Report for Boost Converter at 0.44A Load

Efficiency	95.2%		
Input	15.7W @ 17V		
Output	15W @ 34V		
Ref.	Irms	Ipeak	Dissipation
C8-3	0mA	0mA	0mW
C9	0mA	2mA	0mW
C10	0mA	0mA	0mW
C11	49mA	679mA	0mW
C12	72mA	896mA	0mW
C13	0mA	0mA	0mW
C14	0mA	0mA	0mW
C15	472mA	4305mA	0mW
C22	0mA	0mA	0mW
D3	19mA	211mA	1mW
D4	10mA	180mA	0mW
L2	915mA	1034mA	126mW
M1	645mA	3865mA	29mW
M2	679mA	4835mA	290mW
R9	0mA	0mA	11mW
R10	0mA	0mA	403µW
R11	0mA	0mA	2mW
R12	0mA	0mA	499µW
R13	915mA	1034mA	28mW
R14	0mA	0mA	2µW
R30	0mA	0mA	0µW
U2	81mA	769mA	263mW

Next, the adjustable load dimming feature was taken into account. A system load of 0.01A, a value well below I_{Lmin} , was selected to show that the Burst mode feature still allows the converter to regulate even under the minimum load current. Figure 4-6 illustrates the waveforms for a 0.01A current load. It was observed that the converter, indeed, regulate at 34V output voltage and 8mV voltage ripple, 0.024% ripple. The inductor current clearly experiences the Burst mode operation as it changes its ripple and average values in 100 μ s burst intervals. Each burst was measured to last about 17 μ s. The inductor's switching frequency was measured to be 350 kHz during the burst and 530 kHz during the off time. The Burst mode operation is also seen through the gate voltages that control the switching of the MOSFETs and allow the regulator to function at light loads. The switching frequencies of M1 and M2 are both 350kHz during the bursts and 530 kHz during the off times. Similarly, each burst last for about 17 μ s and repeats every 100 μ s. Table 4.8 displays the simulated efficiency, current, and power dissipation of components for boost converter at 0.01A load.

(a)

(b)

(c)

(d)

Figure 4-6: Boost Converter Waveforms for $V_{in} = 17V$ and $I_O = 0.01A$, (a) Output Voltage Ripple, (b) Inductor Current Ripple, (c) M1 Gate Voltage, (d) M2 Gate Voltage

Table 4-8: Efficiency Report for Boost Converter at 0.01A Load

Efficiency	77.4%		
Input	439mW @ 17V		
Output	340mW @34V		
Ref.	Irms	Ipeak	Dissipation
C8-3	0mA	0mA	0mW
C9	0mA	4mA	0mW
C10	0mA	0mA	0mW
C11	3mA	135mA	0mW
C12	28mA	860mA	0mW
C13	0mA	0mA	0mW
C14	0mA	0mA	0mW
C15	60mA	3694mA	0mW
C22	0mA	0mA	0mW
D3	3mA	133mA	0mW
D4	4mA	183mA	0mW
L2	64mA	248mA	1mW
M1	61mA	3683mA	7mW
M2	68mA	3871mA	41mW
R9	0mA	0mA	11mW
R10	0mA	0mA	403 μ W
R11	0mA	0mA	2mW
R12	0mA	0mA	499 μ W
R13	64mA	248mA	136 μ W
R14	0mA	0mA	1 μ W
R30	0mA	0mA	0 μ W
U2	34mA	772mA	38mW

Figure 4-7 plots the simulation efficiencies against the load current for 17V input. The efficiency trend increases along with the load current. It is observed that the boost converter will operate between 77%-95% efficiencies for loads between 0.01A to 0.44A.

Figure 4-7: Boost Converter Efficiency vs Load Current Simulation for 17V

The boost converter was also simulated for low input voltages when the DC input source is disconnected and the system operates through the batteries. For a nominal single cell battery of 1.2V, the battery pack will supply a minimum voltage of 7.2V. The boost converter was simulated for both 0.44A and 0.01A loads at 7.2V. Table 4-9 summarizes the simulation results for the two loads at 7.2V input. Figure 4-8 displays the simulation efficiencies against the load current for 7.2V input. The efficiency also increases with the load current until about 0.25A load. The curve approaches 92% and then settles down to 90%. Overall, the efficiency curve is observed to operate between 50%-92% efficiencies for loads between 0.01A to 0.44A.

Table 4-9: Load Summary for 7.2V input

Load (A)	0.01	0.44
V_O (V)	34V	34V
ΔV_O (mV)	1	10
I_O (A)	0.086	2.287
ΔI_O (A)	0.161	0.153
Operation	Burst mode	CCM
F_{sw} (kHz)	350	350
Efficiency	50.2%	90.3%
Input	678mW @ 7.2V	16.6W @ 7.2V
Output	340mW @ 34V	15W @ 34V

Figure 4-8: Boost Converter Efficiency vs Load Current Simulation for 7.2V

The boost converter simulations verified the circuit design in section 4.2. It also proved that the Burst mode function works for lower duty cycles of the PWM dimming circuit of the DC light bulb. The simulations demonstrated that the boost converter design is about 90% efficient with 0.44A loads. However, lower loads pull down the efficiency and even further for lower input voltages.

4.4 Charger Circuit Design

The LTC4011 can be adjusted to charge either NiMH or NiCd batteries. It is not advised to charge those batteries while set to a different chemistry. For NiMH charging, the CHEM pin is connected to ground. To switch to NiCd charging, the CHEM pin must be left floating.

To determine the appropriate charging current, we must consider charge rates. Charge rates, or C, represent the battery's charge and discharge rate in a one hour period. For example, a C-rate of 2C will charge twice as fast and need only 30 minutes. Similarly, a C-rate of C/2 will charge slower and requires about 2 hours to fully charge. The charge rate is associated with the battery's capacity in amp-hours, or Ah. For example, a 2,200mAh battery will require a 2.2A charge current to charge at a 1C charge rate. A 2,000mAh battery will require 4A for 2C or 1A for C/2. Battery manufacturers often provide a recommended charge rate for their products. LTC4011 recommends having a charge rate between C/2 and 2C. To find a suitable charge current, we must look at the charge rates of the certain NiMH battery capacities. The range of capacities was chosen as 1,100mAh–2,800mAh. Table 4-10 displays the C/2, 1C, and 2C charge rates of those capacities.

Table 4-10: Charge Rates for Certain Capacities

Capacity (mAh)	C/2 (A)	1C (A)	2C (A)
1100	0.55	1.1	2.2
1200	0.60	1.2	2.4
1300	0.65	1.3	2.6
1400	0.70	1.4	2.8
1800	0.90	1.8	3.6
2000	1.00	2	4
2300	1.15	2.3	4.6
2400	1.20	2.4	4.8
2800	1.40	2.8	5.6

To find a charge current within the C/2 and 2C charge rate range, we look at the highest C/2 current and lowest 2C current. These current values, highlighted above, become the limits to a more specific range. A charge current between 1.4A and 2.2A will sit within the C/2 and 2C range for 1,100mAh-2,800mAh capacities. The charge current was selected to be 2A and can be programmed using a sense resistor. The sense resistance can be calculated using equation 4.12. For a 2A charge current, R_{sense} was calculated to be 50m Ω and placed after the inductor.

$$R_{\text{sense}} = \left(\frac{100 \text{ mV}}{I_{\text{PROG}}} \right) = \left(\frac{100 \text{ mV}}{2 \text{ A}} \right) = 0.050 \Omega \quad (4.12)$$

The battery charging times can also be calculated by dividing the battery capacity by the selected charge current, 2A. For example, a 2,000mAh or 2Ah capacity will take one hour to charge. Table 4-11 presents the charging times, in minutes, for 1,100mAh–2,800mAh capacity range.

Table 4-11: Charging Times

Capacity (mAh)	Time (minutes)
1100	33
1200	36
1300	39
1400	42
1800	54
2000	60
2300	69
2400	72
2800	84

Similar to the boost converter, the LTC4011 utilizes a PWM synchronous buck controller and current sensing. It uses a step down controller to acquire the desired charge current. The buck synchronous switches are denoted as F2 and F3. As stated in section 3.3, the minimum DC input voltage was determined to be 12.3V for 6 cells in series. However, 17V was chosen in case

an expansion for 8 cells in series is desired. The inductor value was calculated using the equation provided in the datasheet, shown below. A 10 μ H inductor was selected for the synchronous buck controller.

$$L > (6.5 * 10^{-6}) * R_{\text{sense}} * V_{\text{DCIN}}; L > 4.7\mu\text{H} \quad (4.13)$$

$$L > (6.5 * 10^{-6}) * (0.05\Omega) * (17\text{V})$$

$$L > 6\mu\text{H}$$

The first charge termination is the charge timer, or maximum fast charge period, set by equation 4.14. For a typical charge of 1C, R_{timer} or R20, was chosen to 49.9 k Ω to set a 1.5 hour fast charge limit and 30 minutes top-off charge. As shown in Table 4-11, the charging times for capacities up to 2,800mAh do not exceed 1.5 hours (90 minutes) showing that the timer will not terminate the charge before the battery is fully charged.

$$R_{\text{Timer}} = \left(\frac{t_{\text{MAX (Hours)}}}{(30 * 10^{-6})} \right) = \left(\frac{1.5}{(30 * 10^{-6})} \right) = 50 \text{ k}\Omega \quad (4.14)$$

The second charge termination is $-\Delta V$, or change in voltage. Because the charger experiences the total battery pack voltage, a cell voltage network must be implemented to provide the average single-cell voltage to be monitored for ΔV charge termination. For the NiMH charger setting, the LTC4011 searches for a -10mV $\pm$ 1.5mV average cell voltage drop. The multiple cell voltage divider is shown in Figure 4-9. R1 was arbitrarily chosen as 5 k Ω . With n being the number of series cells, R2 was calculated to be 25 k Ω . R1 and R2 were designated as R24 and R23, respectively.

$$R_2 = R_1(n - 1) = (5 \text{ k}\Omega)(6 - 1) = 25 \text{ k}\Omega \quad (4.15)$$

Figure 4-9: LTC4011 Multiple Cell Divider [34]

The last charge termination is $\Delta T/\Delta t$, or change in temperature over time. To monitor the battery pack temperature, a thermistor is used and placed as close to the batteries as possible. When the thermistor experiences high temperatures, it creates a short to ground and enabling the charger to terminate its charge. A 5% 10 k Ω NTC thermistor, B57891M0103J000, was selected and used to calculate the appropriate external resistor network. Given $R_0 = 10$ k Ω , $T_0 = 298.15$ K, and $\beta = 3950$ by the thermistor's characteristics, the resistor values were calculated using the design equations in the datasheet. For the NiMH charger setting, the LTC4011 searches for a 1 $^{\circ}\text{C}/\text{min}$ ± 0.14 $^{\circ}\text{C}$ temperature rise. The LTC4011 switches to its top-off charge (C/10) only after the $\Delta T/\Delta t$ charge termination. Figure 4-10 illustrates the external NTC thermistor network where R_0 is the thermistor resistance at T_0 , T_0 is the thermistor reference temperature, and β is the exponential temperature coefficient of resistance. Furthermore, the V_{TEMP} pin can initiate a pause in the charge operation at any time by connecting the pin to ground.

$$R1 = \frac{\beta R_0 T_0^2}{\left(2.461\beta + 4.921T_0 + \frac{T_0^2}{11.46} \right)^2} \quad (4.16)$$

$$R2 = \frac{(R_0 + R3)(\beta(R_0 - R3) - 2(R_0 + R3)T_0)}{\beta\left(\frac{R_0}{7.1} + R3\right) + 2(R_0 + R3)T_0} \quad (4.17)$$

$$R_3 = \frac{R_0 \left(\beta - 2T_0 - \frac{T_0^2}{28.2} \right)}{\beta + 2T_0 + \frac{T_0^2}{28.2}} \quad (4.18)$$

Figure 4-10: LTC4011 External NTC Thermistor Network [34]

Table 4-12 presents the characteristics and calculated resistor values for the B57891M0103J000 NTC thermistor resistor. R4 was designated to R26 and set to 10 k Ω while C1 was designated to C19 and set to 0.1 μ F. Resistors R1, R2, and R3 were designated as R25, R27, and R32, respectively.

Table 4-12: External Thermistor Network, (a) NTC thermistor characteristics, (b) resistor network values

R₀ [Ω]	10 k
T₀ [K]	298.15
β	3950

(a)

R1	R2	R3
9.783 k Ω	26.104 k Ω	261.674 Ω

(b)

Colored LEDs were connected to the LTC4011 status pins to show the controller's status and operating state. A green LED was connected to the READY pin to show when the appropriate operating voltages are present. A yellow LED was connected to the TOC pin to indicate top off charge operation for NiMH batteries. An orange LED was connected to the CHRГ pin to show that the battery is charging. A red LED was connected to the FAULT pin to

indicate a battery or internal charging fault. Table 4-13 summarizes the charger states for the status pins. Figure 4-11 displays the final LTC4011 circuit design.

Table 4-13: LTC4011 Status Pin Summary [34]

READY	FAULT	CHRG	TOC	V _{CDIV}	CHARGER STATE
Off	Off	Off	Off	Off	Off
On	Off	Off	Off	On	Ready to Charge (V _{TEMP} Held Low) or Automatic Recharge
On	Off	On	Off	On	Precharge or Fast Charge (May be Paused)
On	Off	On	On	On	NiMH Top-Off Charge (May be Paused)
On	On	On or Off	On or Off	On	Temperature Limits Exceeded
Off	On	Off	Off	On	Fault State (Latched)

Figure 4-11: LTC4011 Charging Circuit Complete Schematic

4.5 Buck Converter Design

Once again, the buck converter was designed to step down the nominal 48V DC house bus voltage to 17V to meet the charging circuit requirements. It was designed to have a wide

input range of 24V to 60V. 60V was selected as the maximum input voltage due to the LTC3891 input supply voltage rating. As the first circuit in the system, the buck converter considered a variety of scenarios to ensure enough power supply to each circuit. Although the DC light bulb was measured to consume less than 14W, the buck converter was designed to supply power for a system load at 15W. Additionally, the charging circuit will draw more current if the charger is operating.

Because the charging circuit uses a PWM synchronous buck converter, the charger current was found using back calculation. As the battery approaches its fully charged state, the battery pack voltage rises to approximately 9V, or 1.5V per cell. At 9V and a programmed charge current of 2A, the output power of the LTC4011 synchronous buck is 18W. The input power and current of the LTC4011 synchronous buck can be calculated using efficiencies of 80%, 88%, and 95% to signify worst, typical, and best cases. Table 4-14 displays the input power and current for those efficiencies.

$$P_O = I_{\text{charge}} * V_{\text{batt}} = (2A) * (9V) = 18W \quad (4.19)$$

$$P_{\text{in}} = \frac{P_O}{\eta} = \frac{18W}{0.88} = 20.45W \quad (4.20)$$

$$I_{\text{in}} = \frac{P_{\text{in}}}{V_{\text{in}}} = \frac{20.45W}{17V} = 1.2A \quad (4.21)$$

Table 4-14: Calculated Input Power and Current for Charging Circuit Buck Converter

Efficiency, η	P_{in} (W)	I_{in} (A)
0.8	22.50	1.32
0.88	20.45	1.20
0.95	18.95	1.11

For efficiencies as low as 80%, the charger can draw up to 1.32A from the buck. Similarly, the same calculations were applied to the boost converter to estimate its required current. It was observed that the boost converter can draw up to 1.1A, shown in Table 4-15.

$$P_{in} = \frac{P_o}{\eta} = \frac{15W}{0.88} = 17.045W \quad (4.22)$$

$$I_{in} = \frac{P_{in}}{V_{in}} = \frac{17.045W}{17V} = 1.002A \quad (4.23)$$

Table 4-15: Calculated Input Power and Current for Boost Converter

Efficiency, η	Pin (W)	Iin (A)
0.8	18.75	1.10
0.88	17.045	1.002
0.95	15.790	0.928

Therefore, the maximum output current of the LTC3891 buck converter was estimated to be 2.42A by adding the charger and boost currents. However, the buck converter maximum current, I_{MAX} , was set to 5A as a buffer, especially due to the lack of the LTC4011 simulation. Like the boost converter, the switching frequency was set to 350 kHz by connecting the FREQ pin to the system ground. The LTC3891 was also selected for Burst mode operation by connecting ground to the PLLIN/MODE pin. The converter duty cycle can be determined through the buck transfer function shown in equation 4.24.

$$\text{Duty Cycle} = \frac{V_o}{V_{in}} = \frac{17V}{48V} = 0.354 \quad (4.24)$$

For a buck converter, the average output current is equal to the average inductor current. Thus, $I_{Omax} = I_{Lmax} = 5A$. The inductances were calculated for 5%-30% ripple as shown through the equations 4.25 through 4-28. Although the Burst mode operation was selected, lower current ripple was still desired. Table 4-16 presents the inductor current characteristics for various inductances. It further proves that lower % ripples need higher inductance values.

$$\Delta I_L = (\% \text{ ripple}) * I_{Lmax} \quad (4.25)$$

$$I_{Lmin} = \frac{\Delta I_L}{2} \quad (4.26)$$

$$I_{Lpeak} = I_{Lmax} + \frac{\Delta I_L}{2} \quad (4.27)$$

$$L_C = \frac{V_O}{\Delta I_L * f_{sw}} \left(1 - \frac{V_O}{V_{in}}\right) \quad (4.28)$$

Table 4-16: Inductance and Current Characteristics for Buck Inductor Selection

% ripple	ΔI_L (A)	I_{Lmin} (A)	I_{Lpk} (A)	L_c (μH)
0.30	1.5	0.75	5.75	21
0.25	1.25	0.625	5.625	25
0.20	1	0.5	5.5	31
0.15	0.75	0.375	5.375	42
0.10	0.5	0.25	5.25	63
0.05	0.25	0.125	5.125	125

Considering inductor size and availability, 68 μH inductor value was chosen for the buck converter. The selected 68 μH inductor was designed to have a saturation current of 4.9A and 84m Ω DCR. Table 4-17 shows the inductor current characteristics for the selected inductance. The % ripple for 68 μH was found to be 9.2%, a very beneficial feature for lighter loads.

Table 4-17: Inductor Current Characteristics for 68 μH

Inductance (μH)	68
ΔI_L (A)	0.461
% ripple	0.092
I_{Lmin} (A)	0.231
I_{Lpk} (A)	5.23

Like the boost converter, the LTC3891 regulates using current sensing through a sense resistor. The sense resistance was calculated using equation 4.29 and an RC filter was implemented for cleaner sensing. The maximum threshold limit, $V_{sense(max)}$, was set to 75mV by floating the I_{LIM} pin. For an I_{Lpeak} of 5.23A, R_{sense} was calculated to be approximately 14m Ω .

$$R_{sense} = \left(\frac{V_{sense(max)}}{I_{Lmax} + \frac{\Delta I_L}{2}} \right) = \left(\frac{0.075V}{5.23A} \right) = 0.014\Omega \quad (4.29)$$

The output voltage was set using an external feedback resistor divider across the output node. The resistor values were calculated using equation 4.30. Resistor R_B was arbitrarily chosen as 95.3k Ω and R_A was calculated to be 4.7 k Ω . R_B and R_A were designated as R_1 and R_2 ,

respectively. The RUN feature was utilized as an under voltage lockout, or UVLO, using an external resistor divider across the input node. The LTC3891's main control loop halts operation when the RUN pin is pulled below 1.16V. To continue operation, the LTC3891 has a rising threshold of 1.21V at the RUN pin. The falling threshold was set for 24V and the rising threshold was set for 25V. 24V was selected as the minimum voltage input as a -50% voltage swing from the 48V DC house bus. Equations 4.31 and 4.32 show the resistance calculations. Resistor R_B was arbitrarily chosen as 100k Ω and R_A was calculated to be 5.1k Ω . R_B and R_A were designated as R_4 and R_3 , respectively.

$$V_O = 17V = 0.8V \left(1 + \frac{R_B}{R_A}\right) \quad (4.30)$$

$$V_{UVLO(Rising)} = 25V = 1.21V \left(1 + \frac{R_B}{R_A}\right) \quad (4.31)$$

$$V_{UVLO(FALLING)} = 24V = 1.16V \left(1 + \frac{R_B}{R_A}\right) \quad (4.32)$$

The buck soft start is chosen to be about 8ms to soften the output voltage rise. Capacitor C_{SS} can be calculated using the equation below, provided by the datasheet. Capacitor C_{SS} was designated as C5.

$$C_{SS} = t_{SS} \left(\frac{10\mu A}{0.8V}\right) = (0.008s) \left(\frac{10\mu A}{0.8V}\right) = 0.1\mu F \quad (4.33)$$

A Schottky diode, D2, was implemented across the buck diode synchronous switch, Q2, to reduce switching loss during dead time and increase efficiency.

4.6 Buck Converter Simulations

The LTC3891 buck converter complete, final schematic is in Figure 4-12. Ideally, the buck converter will operate at 48V with 3.92A load.

Figure 4-12: LTC3891 Buck Converter Complete Schematic

The buck converter was designed for 5A load, but is only expected to load 2.42A for 80% efficiency of each of the following circuits. Figure 4-13 displays the simulated output voltage ripple, inductor current, M1 gate voltage, and M2 gate voltage. The output voltage regulates at about 17.01V and did not reach steady state until about 8ms due to the 0.1μF soft start capacitor. The output voltage ripple was observed to be about 1mV, less than 0.01% ripple. The inductor current was simulated to have an average value of 2.42A and an RMS of 2.416A. It also illustrates a ripple of 0.46A and a switching frequency of about 350 kHz. The gate voltages for both synchronous switches, Q1 and Q2, were measured to switch at 350 kHz. Table 4-18 displays the simulated efficiency, current, and power dissipation of components for buck converter at 2.42A load.

(a)

(b)

(c)

(d)

Figure 4-13: Buck Converter Waveforms for $V_{in} = 48V$ and $I_O = 2.42A$, (a) Output Voltage Ripple, (b) Inductor Current Ripple, (c) M1 Gate Voltage, (d) M2 Gate Voltage

Table 4-18: Efficiency Report for Buck Converter at 2.42A Load

Efficiency	94.1%		
Input	43.6W @ 48V		
Output	41W @ 16.9V		
Ref.	Irms	Ipeak	Dissipation
C1	172mA	640mA	0mW
C2	122mA	2431mA	0mW
C3	123mA	2418mA	0mW
C4	0mA	0mA	0mW
C5	0mA	0mA	0mW
C6	0mA	0mA	0mW
C7	0mA	0mA	0mW
C8	2mA	5mA	0mW
C21	0mA	0mA	0mW
D1	101mA	2433mA	7mW
D2	105mA	924mA	10mW
L1	2457mA	3061mA	507mW
Q1	1495mA	5733mA	1030mW
Q2	1934mA	3215mA	152mW
R1	0mA	0mA	3mW
R2	0mA	0mA	135μW
R3	0mA	0mA	1mW
R4	0mA	0mA	21mW
R5	2457mA	3061mA	84mW
R6	0mA	0mA	0μW
R28	17mA	17mA	3mW
R29	0mA	0mA	0μW
U1	97mA	1081mA	760mW

The buck converter was simulated for 0.1A load to represent lighter loads. At this load, the converter operates with Burst mode. Figure 4-14 illustrates the waveforms with 0.1A load. The output voltage was measured to be 17.02V with a ripple of 12mV. The bursts last for approximately 569 μ s and occur every 595 μ s. During the burst, the regulator switches at 350 kHz.

(a)

(b)

(c)

(d)

Figure 4-14: Buck Converter Waveforms for $V_{in} = 48V$ and $I_O = 0.1A$, (a) Output Voltage Ripple, (b) Inductor Current Ripple During Burst, (c) M1 Gate Voltage, (d) M2 Gate Voltage

In addition, the buck converter was simulated for 1.32A and 1.1A loads. When the light bulb is at 0% duty cycle, or off, the buck experiences a 1.32A load for battery charging. In the situation that the batteries are not present and a bulb at full load, the buck experiences a 1.1A load. The voltage and current ripples for the 0.1A load is slightly different due to the effects of the Burst mode. It was observed that this also affects the efficiency at low loads. Table 4-19

summarizes the buck results, ripples, and values at various loads. The buck converter's efficiency increases with the load current while maintaining 17V at 350 kHz switching frequency. To conclude, it was observed that the buck converter design is suitable for the system. Figure 4-15 plots the simulation efficiencies against the load current for the buck converter. Once again, the efficiency increases as the load current increases. It is observed that the buck converter will operate between 62.9%-94.2% efficiencies for loads between 0.1A to 2.5A.

Table 4-19: Load Summary for Buck Converter

Load (A)	0.1	1.1	1.32
V_O (V)	17.02	17.02	17.02
ΔV_O (mV)	12	1.9	1.9
I_O (A)	0.101	1.104	1.322
ΔI_O (A)	0.3	0.456	0.458
Operation	Burst Mode	CCM	CCM
F_{SW} (kHz)	350	350	350
Efficiency	62.9 %	92.1 %	92.9%
Input	2.7W @ 48V	20.3W @ 48V	24.2W @ 48V
Output	1.7W @ 17V	18.7W @ 17V	22.5W @ 17V

Figure 4-15: Buck Converter Efficiency vs Load Current Simulation

4.7 Full System Simulations

The full system simulation schematic is shown in Figure 4-16. The charging circuit is simulated by a 1.32A DC load on LTSpice to mimic battery charging operation. The system load represents the light bulb set at full load of 0.44A.

Figure 4-16: Full System Complete Schematic

Figure 4-17 shows the voltage waveforms at the buck and boost outputs. It was observed that the boost converter (blue line) does not reach 34V until 28ms due to the programmed soft start. Similarly, the buck converter (green line) smoothly regulates over 8ms. Both converters were unaffected by the charger load and appear to operate by design.

Figure 4-17: Full System Output Voltage Waveforms

Table 4-20 displays the voltages, currents, and efficiencies for the buck and boost converter for various scenarios. The circuit was simulated for 0.44A system load without battery charging in the event that batteries are not present or the charging is terminated. Next, the system was simulated for 0.2A system load with battery charging for when the DC light bulb is set at approximately 50% PWM duty cycle. Last, the system was simulated for 0A system load with battery charging in the scenario when the DC light bulb is turned off and batteries are present. It was observed that the system's efficiency also increases with the system load. Most importantly, the converter voltages are consistently regulated in all cases. This further proves the validity of the DC flashlight adaptor design.

Table 4-20: Load Summary for the DC Flashlight Adaptor System

System Load (A)	0.44	0.44	0.2	0
Charging	On	Off	On	On
V_{IN} (V)	48	48	48	48
I_{IN} (A)	0.824	0.355	0.658	0.5
$V_{BuckOut}$ (V)	17.02	17.02	17.02	17.02
$I_{BuckOut}$ (A)	2.235	0.915	1.75	1.32
V_O (V)	34.1	34.1	34.1	34.1
I_O (A)	0.44	0.44	0.2	0
Efficiency	83.4%	88%	78.5%	74.9%

Table 4-21 presents the comparison between the design and simulation regulation and efficiency results. The designed system clearly meets the requirements, shown through the simulation results. Table 4-22 shows the system efficiency simulation results for three ideal scenarios. The simulation verifies that the design meets the 80% requirement for each case. Furthermore, the system appears to be most efficient when using the batteries as the system source.

Table 4-21: Summary of Design and Simulation Results

	Design		Simulation		
	Buck	Boost	Buck	Boost	
				7.2V	17V
Load Regulation	2%	5%	0.1%	0%	0%
Line Regulation	2%	5%	0%	2.2%	0%
Efficiency	90%	90%	94.1%	90.3%	95.2%
$\%V_{Opp}$	2%	5%	0.006%	0.02%	

Table 4-22: Design and Simulation System Efficiencies

	Without Battery	With Battery	Only Battery
Design	80%	80%	80%
Simulation	88%	83.4%	90.3%

Chapter 5: Hardware Design and Results

5.1 PCB Layout Design

The DC flashlight adaptor system was implemented onto a custom four layer PCB for design evaluation. The PCB was designed on a MiniBoardPro 4-Layer Serice using ExpressPCB [37]. The exact board size was given to be 3.8" x 2.5", or 96.52mm x 63.5mm. The PCB utilizes four layers including two copper layers, a ground plane, and a power plane. Figure 5-1 illustrates the pads, traces, and vias for each of the four layers.

Figure 5-1: ExpressPCB Four Layer Design, (a) Top Signal Plane, (b) Bottom Signal Plane, (c) Ground Plane, (d) Power Plane.

Because of the complex circuitry, at least two copper layers are required to provide paths for overlapping traces. The ground plane offers a larger area for grounding to decrease noise

from the high frequency switching of the converters. Each of the three circuits are intentionally grouped together and placed in order from left to right. This allows the shortest path of power to reduce as much loss and noise within the circuit. Figure 5-2 outlines the buck converter, charging circuit, and boost converter on the PCB. Large pads were added for the battery pack and NTC thermistor connections to the charging circuit. Additionally, pads at the buck converter and charging circuit outputs were placed for loading and testing purposes.

Figure 5-2: DC Rechargeable Lighting System PCB layout

Figure 5-3 displays the four-layer PCB after being printed and manufactured by ExpressPCB. To reduce the size of the layout to as small as possible, the PCB can be cut to size. The dimensions were measured to be about 3.58" x 1.96", or 91mm x 50mm, shown Figure 5-4.

(a)

(b)

Figure 5-3: Manufactured PCB, (a) Top Signal Plane, (b) Bottom Signal Plane

Figure 5-4: Reduced Dimensions for PCB

Figure 5-5 presents the final circuit board without the battery and NTC thermistor connected. The hardware implementation tested each circuit individually to ensure proper operation of each subsystem. Next, the buck and charger were connected through a 0Ω resistor R7 and later expanded with the boost converter through resistor R8. Once the DC flashlight adaptor system proved to work, the DC light bulb was added as the system load.

(a)

(b)

Figure 5-5: Final PCB with Components, (a) Top View, (b) Side View

5.2 Buck Test Set Up and Results

The LTC3891 buck converter was set up and tested individually. Table 5-1 lists the testing equipment used for data measurement. The DC power supply provided the required input voltage while the multimeters measured the desired currents and output voltage for efficiency calculations. The DC electronic load was adjusted to emulate various current loads and the

oscilloscope was used to observe gate voltage waveforms. Figure 5-6 illustrates the buck converter test set up.

Table 5-1: Buck Converter Equipment Used for Efficiency and Regulation

Purpose	Equipment	Manufacture	Model
V_{in}	DC Power Supply	MPJA	9319-PS
V_{in}	Multimeter	BK Precision	5491A
I_{in}	Multimeter	GW	GDM-8245
V_o	Multimeter	Extech Instruments	MN35
I_o	Multimeter	Rigol	DM3052
DC Load	DC Electronic Load	BK Precision	8540
Duty Cycle	Oscilloscope	GW	GDS-2204

Figure 5-6: Buck Converter Testing Set Up

The input voltage was set at 48V to emulate the DC house bus. The load current was increased from no load to 2.5A by increments of 0.1A. It is important to test the buck load up to 1.1A to ensure that the converter can supply without charging and only to the boost converter. Similarly, a load up to 1.32A was noted to ensure the converter can supply to the charger without a system load. Next, the buck converter was tested up to 2.42A load to test if the buck converter can handle both the battery charging and the DC light bulb load. Furthermore, it was pushed to

2.5A for worst case situations. Table 5-2 shows the buck converter efficiency calculations for loads up to 2.5A.

Table 5-2: Buck Converter Power Measurements and Efficiencies

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	V_O (V)	I_O (A)	P_O (W)	Efficiency (%)
48.4	0	0	17	0	0	0
48.1	0.046	2.23	16.9	0.100	1.69	76
48.4	0.091	4.39	16.9	0.200	3.38	77
48.4	0.137	6.62	16.9	0.299	5.05	76
48.5	0.181	8.78	16.9	0.400	6.76	77
48.5	0.220	10.66	16.9	0.500	8.45	79
48.6	0.262	12.74	16.9	0.599	10.12	79
48.5	0.303	14.68	16.9	0.700	11.83	81
48.6	0.343	16.65	16.9	0.799	13.50	81
48.6	0.382	18.57	16.9	0.899	15.19	82
48.6	0.419	20.35	16.9	0.999	16.88	83
48.4	0.465	22.49	16.9	1.099	18.57	83
48.4	0.505	24.45	16.9	1.199	20.26	83
48.3	0.545	26.32	16.9	1.299	21.95	83
48.3	0.585	28.24	16.9	1.399	23.64	84
48.0	0.635	30.48	16.8	1.499	25.18	83
48.3	0.662	31.97	16.9	1.599	27.02	85
48.0	0.716	34.35	16.8	1.699	28.54	83
48.0	0.758	36.40	16.8	1.799	30.22	83
47.9	0.800	38.32	16.8	1.899	31.90	83
47.8	0.838	40.06	16.8	1.999	33.58	84
48.2	0.879	42.37	16.7	2.099	35.05	83
48.1	0.917	44.10	16.7	2.199	36.72	83
48.0	0.958	45.98	16.7	2.299	38.39	83
48.3	0.988	47.73	16.8	2.399	40.30	84
48.2	1.030	49.65	16.8	2.499	41.98	85

It was observed that the LTC3891 has an efficiency range between 76%-85%. The results prove better than the simulations at low loads such as 0.1A, but are lower at higher loads by about 9%. Figure 5-7 illustrates the relationship between load current and efficiency. The efficiency values fluctuate but generally increase with the load current shown by the black trend line. Although the inductor saturation current sits much higher than the maximum output current,

the inductor emitted heat during high load testing. The heat could have been the result of the 84mΩ DC resistance dissipating power and reducing efficiency.

Figure 5-7: LTC3891 Buck Converter Efficiency vs Load Current

The load regulation was acquired using equation 5.1 [38]. $V_{(\min\text{-load})}$ and $V_{(\max\text{-load})}$ are the output voltages at the minimum and maximum loads. $V_{(\text{nom-load})}$ is the nominal regulated voltage set at 17V. For a minimum load of 0.1A, the voltage was measured as 16.9V. A maximum load of 2.5A provides an output voltage of 16.8V. Using these values, the load regulation was calculated to be 0.6%.

$$\% \text{ Load Regulation} = 100\% \left(\frac{V_{(\min\text{-load})} - V_{(\max\text{-load})}}{V_{(\text{nom-load})}} \right) \quad (5.1)$$

The line regulation was obtained using equation 5.2 [38]. The nominal voltage input was set to 48V to represent the DC house bus. The $V_{(\max\text{ input})}$ and $V_{(\min\text{ input})}$ are the output voltages for about a 17% voltage swing from the nominal input voltage. The output voltage was measured to be 16.9V with a 40V input voltage and 2.42A load. Similarly, a 56V input voltage produces 16.9V as well. Therefore, the line regulation was calculated to be 0%. Table 5-3 shows the load and line regulation results.

$$\% \text{ Line Regulation} = 100\% \left(\frac{V_{(\text{max input})} - V_{(\text{min input})}}{V_{(\text{nom-input})}} \right) \quad (5.2)$$

Table 5-3: Load and Line Regulation of the LTC3891 Buck Converter

% Load Regulation	0.6%
% Line Regulation	0%

Overall, the LTC3891 Buck Converter validates the subsystem design. Although the efficiencies were lower than the simulation, the buck converter still operates at an exceptional efficiency. The load and line regulations of less than 1% further verifies the switching regulator.

5.3 Charger Test Set Up and Results

Next, the LTC4011 charging circuit was implemented and tested. Table 5-4 presents the equipment used for data measurement. The DC power supply was set for 17V acting as the buck converter output. The multimeters were set up to measure input, output, and battery values. The DC electronic load simulated the currents drawn by the boost converter.

Table 5-4: Charging Circuit Equipment Used for Efficiency and Regulation

Purpose	Equipment	Manufacture	Model
V_{in}	DC Power Supply	MPJA	9319-PS
I_{in}	DC Power Supply	MPJA	9319-PS
V_o	Multimeter	Extech Instruments	MN35
I_o	Multimeter	Rigol	DM3052
V_{Batt}	Multimeter	BK Precision	5491A
I_{charge}	Multimeter	GW	GDM-8245
DC Load	DC Electronic Load	BK Precision	8540

The battery pack was implemented for the charging circuit. An 8 AA battery holder was used to hold 6 AA NiMH 2,500mAh batteries shown in Figure 5-8. The NTC thermistor was taped beside the battery pack and connected to the board through 18 AWG wires. Figure 5-9 illustrates the charging circuit equipment set up.

Figure 5-8: Battery Pack

Figure 5-9: Charging Circuit Testing Set Up

Without the DC input source, the output voltage is taken from the battery pack voltage.

With the presence of the DC input source, the output voltage is taken from the 17V input and the battery charging begins. The ready (green) and charge (orange) LEDs turn on to signify proper charging requirements and charging operation. The current load was increased from no load to 1.4A in 0.1A increments. It is important to note the 1.1A load to simulate the estimated maximum boost current. Table 5-5 shows the charging circuit efficiency calculations with a charging battery. The input power is the product of the input voltage and current while the output

power is the product of the output voltage and load current. The power at the battery load, P_{Batt} , is the product of the charge current and the battery voltage. The system output power and P_{Batt} was added to provide the total consumed power, P_{Tot} . The efficiency was calculated as the total consumed power divided by the input power.

Table 5-5: Charging Circuit Power Measurements and Efficiencies

V_{In} (V)	I_{IN} (A)	P_{IN} (W)	V_{Batt} (V)	I_{CHRG} (A)	V_{O} (V)	I_{O} (A)	P_{Tot} (W)	Efficiency (%)
16.97	1.22	20.77	7.373	2.01	16.6	0.000	14.82	71.3
16.95	1.33	22.54	7.414	2.01	16.6	0.100	16.56	73.5
16.93	1.43	24.21	7.487	2.01	16.6	0.200	18.37	75.9
16.92	1.54	26.06	7.548	2.01	16.5	0.300	20.12	77.2
16.89	1.65	27.87	7.595	2.01	16.5	0.400	21.87	78.5
16.88	1.76	29.71	7.651	2.01	16.5	0.500	23.63	79.5
16.86	1.86	31.36	7.699	2.01	16.4	0.600	25.31	80.7
16.84	1.96	33.01	7.738	2.01	16.4	0.700	27.03	81.9
16.82	2.07	34.82	7.778	2.01	16.4	0.800	28.75	82.6
16.80	2.17	36.46	7.805	2.01	16.4	0.900	30.45	83.5
16.78	2.28	38.26	7.845	2.01	16.4	1.000	32.17	84.1
16.76	2.38	39.89	7.877	2.01	16.4	1.099	33.86	84.9
16.74	2.49	41.68	7.898	2.01	16.3	1.200	35.43	85.0
16.72	2.59	43.30	7.935	2.01	16.3	1.299	37.12	85.7
16.71	2.70	45.12	7.958	2.01	16.3	1.400	38.82	86.0

Figure 5-10: LTC4011 Charger Efficiency vs Load Current

Figure 5-10 illustrates the relation between the charger's efficiency against load current. It was observed that the efficiency increases consistently with the load current. The system efficiency rises as high as 86% for 1.1A load and battery charging. It can be observed that the charge current sits consistently at 2.01A and is unaffected by the load current. The battery pack voltage increased from 7.373V to 7.958V within a 10 minute testing period.

In addition to the efficiency calculations, the charging circuit was also tested for its charging termination. The charger was set at 1.1A load with 17V input and monitored until the charge was terminated. The DC input source was turned on and the charger proceeded to charge. Figure 5-11 displays the ready and charge LEDs turned on during charging. As the battery is charged at 2.01A, the input current was measured to be 2.29A. The output voltage was seen to be 16.4V at 1.099A load current. 8 minutes later, the charge LED was then turned off and the charge current decreased to 0A. Both input and output currents were measured to be 1.109A, showing that the charger does not draw current without the charging operation. During an 8 minute charge time, the battery voltage increased to 8.583V and the charging circuit output was measured to be 8.1V. Table 5-6 summarizes the voltages before and after the charging operation.

Table 5-6: Summary of Charging Operation with 1.1A load

Time	V_{Batt} (V)	V_O (V)
t_0	7.992	7.4
$t_0 + (8 \text{ minutes})$	8.583	8.1

Figure 5-11: Charging Operation

The power path network was tested by applying the DC load without the 17V DC input present. The electronic load was adjusted to 1.1A to simulate the boost converter at full load. The discharge current from the battery pack was observed to be -1.124A to supply the all of the load current. The negative sign implies discharging current flowing in the opposite direction. After 11 minutes at 1.1A load, the battery voltage decreases to 7.795V, a 0.788V difference. Table 5-7 summarizes the discharging operation.

Table 5-7: Summary of Discharging Operation

Time	V_{Batt} (V)	V_{O} (V)
t_0	8.583	8.1
$t_0 + (11 \text{ minutes})$	7.795	7.3

Next, the charging operation was tested without a load present in the scenario that the DC light bulb is turned off. At this battery voltage, the battery pack is eligible for charging and the ready and charge lights turn on when the DC input is applied. The input current was measured to be 1.203A, the total current drawn during the charging operation. 10 minutes later, the TOC LED turned on symbolizing top off charge operation. The charge current decreased to 0.21A and the input current lowered to 0.145A. Exactly 30 minutes later, the charge and TOC LEDs turn off

and the charge current drops to 0A. The battery pack was charged to 8.524V, a 0.729V difference, within a period of 41 minutes. Table 5-8 summarizes the charging operation without the system load.

Table 5-8: Summary of Charging Operation Without Load

Time	V_{Batt} (V)	V_o (V)
t_0	7.795	7.3
$t_0 + (41 \text{ minutes})$	8.524	7.9

These results validate the charging circuit design. Both charging and discharging operations were proven to function correctly illustrating the purpose of the synchronous buck converter and the power path network. Furthermore, the charging circuit operates at high efficiencies especially at higher system loads.

5.4 Boost Test Set Up and Results

The LTC3786 boost converter was set-up and tested as the final subsystem. Table 5-9 lists the testing equipment used for data measurement. The DC power supply was set to supply 17V for the case that the system is connected to the DC house bus. Then, it was adjusted to 7.2V for the case that the system is disconnected from the DC house bus and using the battery pack as the system source. The multimeters were set to measure the desired input and output values for efficiency calculations. Figure 5-12 presents the boost converter test set up.

Table 5-9: Boost Converter Equipment Used for Efficiency and Regulation

Purpose	Equipment	Manufacture	Model
V_{in}	DC Power Supply	MPJA	9319-PS
V_{in}	Multimeter	Agilent Technologies	U3401A
I_{in}	Multimeter	GW	GDM-8245
V_o	Multimeter	Extech Instruments	MN35
I_o	Multimeter	Rigol	DM3052
DC Load	DC Electronic Load	BK Precision	8540
Duty Cycle	Oscilloscope	GW	GDS-2204

Figure 5-12: Boost Converter Testing Set Up

First, the boost was set up and tested for 17V input voltage. The DC electronic load was adjusted from 0.01A to 0.44A in 0.05A increments. This load current represents the current drawn by the DC light bulb. A full load of 0.44A signifies a 15W 34V bulb. The boost converter was pushed up to 0.5A load current. Table 5-10 shows the boost converter efficiency calculations for loads up to 0.5A. The output voltage is regulated between 33.9V-34.1V and the actual efficiency is observed to be 89.8% at 0.44A load. This is only 5.4% below the simulated efficiency of 95.2%. It is noted that at a low load of 0.01A, the boost converter operates at 77.9% which is slightly higher than the simulated 77.4%. Figure 5-13 illustrates the relationship between load current and efficiency. The efficiency values consistently increase with the load current.

Table 5-10: Boost Converter Power Measurements and Efficiencies with 17V

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	V_O (V)	I_O (A)	P_O (W)	Efficiency (%)
17.12	0.023	0.39	34.1	0.009	0.31	77.9
17.10	0.113	1.93	34.1	0.05	1.71	88.2
17.08	0.226	3.86	34	0.1	3.40	88.1
17.06	0.336	5.73	34	0.149	5.07	88.4
17.04	0.448	7.64	34	0.199	6.77	88.6
17.02	0.559	9.52	34	0.249	8.47	89.0
17.00	0.669	11.37	34	0.299	10.17	89.4
16.99	0.779	13.23	34	0.349	11.87	89.7
16.97	0.888	15.07	33.9	0.399	13.53	89.8
16.95	0.978	16.58	33.9	0.439	14.88	89.8
16.93	1.103	18.67	33.9	0.499	16.92	90.6

Figure 5-13: LTC3786 Boost Converter Efficiency vs Load Current with 17V

Next, the boost converter was tested for 7.2V input to simulate a low battery pack voltage. Table 5-11 shows the boost converter efficiency calculations for loads up to 0.44A. The boost converter operates at 84.5% efficiency at 0.44A load. This is 5.8% difference from the boost converter simulation with 90.3% at full load. For 0.01A load, the efficiency is 66.3% which is much higher than the simulated 50.2%. Figure 5-14 shows the relationship between load current and efficiency. Similar to the 17V input voltage, the converter efficiency consistently increases with the load current.

Table 5-11: Boost Converter Power Measurements and Efficiencies with 7.2V

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	V_O (V)	I_O (A)	P_O (W)	Efficiency (%)
7.21	0.064	0.46	34	0.009	0.31	66.3
7.16	0.308	2.21	34	0.05	1.70	77.0
7.11	0.611	4.34	34	0.1	3.40	78.3
7.06	0.908	6.41	33.9	0.149	5.05	78.8
7.01	1.167	8.18	33.9	0.199	6.75	82.4
6.96	1.441	10.04	33.9	0.249	8.44	84.1
6.91	1.729	11.95	33.9	0.299	10.14	84.8
6.86	2.028	13.91	33.9	0.349	11.83	85.0
6.80	2.348	15.97	33.9	0.399	13.53	84.7
6.78	2.522	17.09	32.9	0.439	14.44	84.5

Figure 5-14: LTC3786 Boost Converter Efficiency vs Load Current with 7.2V

The load regulation was obtained for 17V input. $V_{(nom-load)}$ is the nominal regulated voltage set at 34V. For a minimum load of 0.01A, the voltage was measured at 34.1V. A maximum load of 0.44A provides an output voltage of 33.9V. Using equation 5.1, the load regulation was calculated to be 0.59%. Next, the load regulation for 7.2V input was calculated. For a minimum load of 0.01A, the voltage showed at 34V. A maximum load of 0.44A provides an output voltage of 32.9V. Then, the load regulation was calculated to be 3.24%.

$$\% \text{ Load Regulation}_{(17V)} = 100\% \left(\frac{34.1V - 33.9V}{34V} \right) = 0.59\%$$

$$\% \text{ Load Regulation}_{(7.2V)} = 100\% \left(\frac{34V - 32.9V}{34V} \right) = 3.24\%$$

Next, the line regulation was obtained for both input voltages using equation 5.2. For 17V nominal voltage, the input voltage was adjusted with a 1V swing. The $V_{(\text{max input})}$ and $V_{(\text{min input})}$ are the output voltages for the 18V and 16V inputs. For 7.2V nominal voltage, the input was adjusted with a 0.8V swing. The $V_{(\text{max input})}$ and $V_{(\text{min input})}$ are the output voltages for the 8V and 6.4V inputs. Table 5-12 shows the load and line regulation results.

$$\% \text{ Line Regulation}_{(17V)} = 100\% \left(\frac{33.9V - 33.9V}{34V} \right) = 0\%$$

$$\% \text{ Line Regulation}_{(7.2V)} = 100\% \left(\frac{33.9V - 31.1V}{34V} \right) = 8.24\%$$

Table 5-12: Load and Line Regulations of the LTC3786 Boost Converter

V_{IN} (V)	17	7.2
% Load Regulation	0.03%	3.24%
% Line Regulation	0%	8.24%

The LTC3786 boost converter functions well and efficiently with a 17V input voltage. However, the converter does not work well with lower input voltages such as 7.2V. While the DC input supply is present, the boost converter is able to step up the voltage to regulate at the desired 34V. When the DC input supply is disconnected, the system uses the battery pack as the primary source.

5.5 Buck and Charger Test Set Up and Results

The system is slowly pieced together starting with the first two circuits. The buck converter and the charging circuit were connected using a 0Ω resistor R7. The set up was

identical to the charging circuit set up with the implementation of the buck converter. Figure 5-15 illustrates the PCB connections for the buck and charger test set up.

Figure 5-15: Buck and Charger Hardware Testing Set Up

First, the circuit was tested without a battery connected. This eliminates the charging operation and any power consumption by the charging buck converter. The system load, representing the boost converter input current, was slowly increased to 1.1A and then pushed higher to 1.5A. Table 5-13 shows the power measurements and efficiencies at specific loads. The input power was calculated from the input voltage and current of the buck converter. The total output power was calculated by adding the powers at the battery and the charger output. In this case, the total output power is equal to the power at the charger output because the battery is not connected.

Table 5-13: Buck and Charger Power Measurements and Efficiencies Without Battery

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	V_{Batt} (V)	I_{CHRG} (A)	V_O (V)	I_O (A)	P_{Tot} (W)	Efficiency (%)
48.1	0.0446	2.145	0	0	16.46	0.1	1.65	76.7
48	0.4233	20.318	0	0	16.06	1.1	17.65	86.9
47.9	0.5715	27.374	0	0	15.93	1.5	23.88	87.2

The battery is connected and the circuit is measured for the same values. The charging operation is turned on due to the presence of batteries and the charging buck converter begins to consume power. The buck and charger measurements with the battery are summarized in Table 5-14 for specific loads. As the load was increased to 0.6A, it was observed that the buck and charger outputs began to drop along with the charge current. Meanwhile, the inductor was detected to increase in temperature, a valid reason for this current limit. The relatively low efficiency could possibly be the result of the heated inductor.

Table 5-14: Buck and Charger Power Measurements and Efficiencies With Battery

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	V_{Batt} (V)	I_{CHRG} (A)	V_O (V)	I_O (A)	P_{Tot} (W)	Efficiency (%)
47.9	0.524	25.11	7.59	2.01	16.79	0.1	16.93	67.4
47.8	0.692	33.07	7.65	2.01	16.15	0.6	25.07	75.8
47.7	0.576	27.46	7.74	1.305	9.49	1.1	20.54	74.8

Without the charging operation, the two circuits function properly even beyond full load. When the charging operation is added, the system is limited to 0.6A which is slightly over half of full load.

5.6 DC Flashlight Adaptor Test Set Up and Results

The last subsystem is added to the buck and charger to produce the complete DC flashlight adaptor circuit. Figure 5-16 presents the PCB connections for the complete system test set up.

Figure 5-16: Complete System Testing Set Up

Once again, the circuit was tested without a battery to eliminate the charging operation. The system load, representing the DC light bulb, was adjusted to 0.5A in 0.05A increments. The power measurements and efficiencies are shown in Table 5-15. The efficiency rises as the load current increases to full load. At full load, the system operates at around 81.7% efficiency.

Table 5-15: Complete System Power Measurements and Efficiencies Without Battery

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	V_{Batt} (V)	I_{CHRG} (A)	V_O (V)	I_O (A)	P_{Tot} (W)	Efficiency (%)
48.15	0.003	0.14	0	0	34.1	0.0002	0.01	5.6
48.14	0.012	0.58	0	0	34.1	0.009	0.31	53.1
48.14	0.051	2.46	0	0	34.1	0.05	1.71	69.4
48.13	0.1	4.81	0	0	34	0.1	3.40	70.6
48.13	0.148	7.12	0	0	34	0.149	5.07	71.1
48.12	0.189	9.09	0	0	34	0.199	6.77	74.4
48.12	0.23	11.07	0	0	34	0.249	8.47	76.5
48.11	0.271	13.04	0	0	34	0.299	10.17	78.0
48.11	0.312	15.01	0	0	34	0.349	11.87	79.1
48.10	0.353	16.98	0	0	34	0.399	13.57	79.9
48.10	0.385	18.52	0	0	34	0.439	14.93	80.6
48.09	0.432	20.77	0	0	34	0.499	16.97	81.7

The next set of testing includes the battery pack and the charging operation. Because of the buck and charger results, the system load was only increased to 0.2A. However, the load was slowly increased and eventually reached 0.4A load current. Table 5-16 summarizes the power measurements and efficiencies with the charging operation. During the charging operation, the DC flashlight adaptor operates at 81.6% at 0.4A load. The efficiency trend was observed to increase with the load current.

Table 5-16: Complete System Power Measurements and Efficiencies With Battery

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	V_{Batt} (V)	I_{CHRG} (A)	V_O (V)	I_O (A)	P_{Tot} (W)	Efficiency (%)
48.08	0.505	24.28	9.95	2.01	34.2	0.0002	20.02	82.5
48.07	0.516	24.80	10.03	2.01	34.1	0.009	20.48	82.6
48.06	0.555	26.67	10.11	2.01	34.1	0.05	22.03	82.6
48.05	0.6	28.83	10.15	2.01	34.1	0.1	23.81	82.6
48.05	0.643	30.90	10.19	2.01	34	0.149	25.55	82.7
48.04	0.687	33.00	10.22	2.01	34	0.199	27.31	82.7
48.04	0.731	35.11	10.23	2.01	34	0.249	29.04	82.7
48.03	0.774	37.17	10.23	2.01	34	0.299	30.74	82.7
48.02	0.819	39.33	10.22	2.01	34	0.349	32.41	82.4
48.02	0.87	41.77	10.21	2.01	34	0.399	34.09	81.6

Lastly, the DC input source was turned off to simulate system flashlight operation. The battery pack voltage becomes the system source while its discharge current becomes the input current. Table 5-17 presents the power measurements and efficiencies during flashlight operation. It was observed that the complete system operates at 82.8% efficiency at full load.

Table 5-17: Complete System Power Measurements and Efficiencies With Only Battery

V_{Batt} (V)	$I_{DISCHRG}$ (A)	P_{IN} (W)	V_O (V)	I_O (A)	P_O (W)	Efficiency (%)
8.67	0.003	0.03	34.1	0.0002	0.01	32.0
8.63	0.05	0.43	34.1	0.009	0.31	71.1
8.5	0.251	2.13	34	0.05	1.70	79.7
8.33	0.507	4.22	34	0.1	3.40	80.5
8.16	0.773	6.31	33.9	0.149	5.05	80.1
7.97	1.033	8.23	33.9	0.199	6.75	81.9
7.75	1.298	10.06	33.9	0.249	8.44	83.9
7.53	1.593	12.00	33.9	0.299	10.14	84.5
7.28	1.931	14.06	33.9	0.349	11.83	84.2
6.9	2.346	16.19	33.9	0.399	13.53	83.6
6.72	2.525	16.97	32	0.439	14.05	82.8

5.7 DC Portable Lighting System Test Set Up and Results

The DC light bulb was added to complete the DC rechargeable lighting system. A multimeter was placed between the flashlight adaptor and the DC light bulb to measure the output current to half load, around 0.2A, and full load, 0.44A. The output current was controlled by the dimmer of the DC light bulb. The same procedure as the previous section was used to test with the DC light bulb. First, the system was tested without a connected battery and charging operation. With the dimmer set for 100%, the output current was measured to be 0.391A. Table 5-18 shows the power measurements and efficiency for 50% and 100% load. Figure 5-17 illustrates the system set up and the light bulb at full load without batteries. Without the charging operation, the system runs at 79.5% efficiency at full load.

**Table 5-18: Complete System Power Measurements and Efficiencies at Half and Full load
(No Battery)**

V_{In} (V)	I_{IN} (A)	P_{IN} (W)	V_{Batt} (V)	I_{CHRG} (A)	V_O (V)	I_O (A)	P_{Tot} (W)	Efficiency (%)
48.09	0.181	8.70	0	0	34	0.198	6.73	77.3
48.06	0.347	16.68	0	0	33.9	0.391	13.25	79.5

Figure 5-17: DC Rechargeable Lighting System Set Up at Full Load Without Batteries

Next, the battery pack was implemented and measured for efficiency at full load. Table 5-19 displays the power measurements and efficiency for half and full load with batteries. Figure 5-18 illustrates the system set up and the light bulb at full load with the charging operation. The system is observed to operate at 82.3% efficiency at both half and full load.

Table 5-19: Complete System Power Measurements and Efficiencies at Half and Full Load (With Battery)

V_{IN} (V)	I_{IN} (A)	P_{IN} (W)	V_{Batt} (V)	I_{CHRG} (A)	V_O (V)	I_O (A)	P_{Tot} (W)	Efficiency (%)
48.04	0.682	32.76	9.82	2.01	34	0.212	26.95	82.3
48.02	0.842	40.43	9.98	2.01	34	0.388	33.27	82.3

Figure 5-18: DC Rechargeable Lighting System With Batteries at Full Load

The DC input source was turned off and the power path network switches to the battery for power. Table 5-20 presents the power measurements and efficiency for half and full loads. During the flashlight operation, the complete system is measured to operate at 82.9%.

**Table 5-20: Complete System Power Measurements and Efficiencies at Half and Full Load
(With Only Battery)**

V_{Batt} (V)	I_{DISCHRG} (A)	P_{IN} (W)	V_{O} (V)	I_{O} (A)	P_{O} (W)	Efficiency (%)
7.8	1.127	8.79	33.9	0.213	7.22	82.1
6.89	2.298	15.83	33.9	0.387	13.12	82.9

5.8 Summary of Hardware Results

Overall, each subsystem was tested individually and proved to fulfill its purposes. Each individual circuit functions properly and manages to maintain a respectable efficiency. The buck converter tends to overheat at high loads, eventually affecting the voltage regulation. However, the three circuits were implemented and proven to work together with efficiencies up to 82.3%. The charging operation works with the proper input voltage and charge terminations. Most

importantly, the system is able to operate without a DC input voltage present which verifies its portability as a rechargeable flashlight. Figure 5-19 displays the Portable DC Light Bulb system with a DC input and charging operation. Figure 5-20 illustrates the Portable DC Light Bulb system operating on batteries at 100% DC light bulb load.

Figure 5-19: Final Portable DC Light Bulb System in Charging Operation

Figure 5-20: Final Portable DC Light Bulb System in Flashlight Operation

At full load of 2.5A, the buck converter operates at 85% efficiency. Its load and line regulations were measured to be 0.6% and 0% respectively. The voltage ripple was measured to be 180mV which is 1.1% of the 17V output voltage.

The boost converter was measured for both nominal input cases. With a 17V input, the boost converter operates at 90.6% and meets the desired 90% design requirement. The load and line regulations were measured to be 0.6% and 0% respectively. With a 7.2V input, the converter operates at 85% efficiency. The load regulation was measured at 3.2% but still meets the 5% requirement. However, the boost line regulation was measured to be 8.2%, slightly over the desired 5% design requirement. This is the result of a very low input voltage and higher current. For both cases, the voltage ripple was measured to be 80mV which is 0.2% of the 34.15V output voltage. Table 5-21 displays the design, simulation, and hardware result comparisons.

Table 5-21: Summary of Design, Simulation, and Hardware Results

	Design		Simulation			Hardware		
	Buck	Boost	Buck	Boost		Buck	Boost	
				7.2V	17V		7.2V	17V
Load Regulation	2%	5%	0.1%	0%	0%	0.6%	3.2%	0.6%
Line Regulation	2%	5%	0%	2.2%	0%	0%	8.2%	0%
Efficiency	90%	90%	94.1%	90.3%	95.2%	85%	84.5%	90.6%
% V_{Opp}	2%	5%	0.006%	0.02%		1.1%	0.2%	

When the system is connected to the DC House bus, the system operates at 79.5% efficiency at full load. This is slightly lower than the desired 80% system efficiency requirement. When the battery is attached and charging operation is initiated, the system operates at 82.3% at full load which is easily above the 80% limit. Furthermore, the system efficiency rises slightly to 82.9% at full load when the system is disconnected from the DC House bus. Table 5-22 summarizes the overall system design and hardware results.

Table 5-22: Design, Simulation, and Hardware System Efficiencies

	Without Battery	With Battery	Only Battery
Design	80%	80%	80%
Simulation	88%	83.4%	90.3%
Hardware	79.5%	82.3%	82.9%

Chapter 6: Conclusion and Future Consideration

6.1: Summary and Conclusion

This particular thesis focuses on the design and implementation of the Portable DC Light Bulb for Cal Poly San Luis Obispo's DC House Project. The Portable DC Light Bulb system highlights the NiMH battery charging circuit, buck converter, and boost converter. The system is intended as a flashlight adaptor placed in between the previously designed DC light bulb and its screw base. The adaptor adds a portability feature to the DC light bulb to provide lighting wherever the user pleases. The Portable DC Light Bulb system is designed to meet specific electrical requirements while maintaining high efficiencies.

The proposed system fulfills the electrical requirements of the DC House's DC light bulb. The system is able to supply power to the DC light bulb while operating on either the 48V DC house bus or the battery pack. The DC Portable Lighting System is designed to operate with a wide input voltage range of 24V-60V but tested only between 40V-58V. The DC Portable Lighting System's boost converter regulates a 34V output to fit within the DC light bulb input voltage range of 33V-63V.

Furthermore, the charging circuit of the Portable DC Light Bulb system is proven to perform the programmed charging operation and termination. The power path network of the charging circuit ensures that the boost converter and its load are powered at all times. With a DC input supply present, the proposed system initiates charging operation while the DC light bulb stays lit. As the system is disconnected from the 48V DC house bus, it begins to perform as a DC LED flashlight powered by the charged battery pack. Charge terminations that include the timer, $-\Delta V$, and $\Delta T/\Delta t$, are implemented to offer maximum battery charging protection from overcharging.

Each sub-circuit was designed, simulated, implemented, and analyzed for functionality and efficiency. The buck converter operates at 85% for full load with 48V input. The charging circuit operates at 86% for full load and charging operation. The boost converter operates at 89.8% at full load and 17V input. With a 7.2V input, the boost converter operates at 84.5% at full load.

The three circuits were connected and tested with the DC light bulb to obtain efficiencies. Without the battery, the system operates at 79.5% at full load. When the battery is connected, charging operation is initiated and the system operates at 82.3% at full load. Lastly, the proposed system operates at 82.9% at full load when disconnected to the DC house bus. Although the system efficiencies are lower than simulated, this thesis provides proof of concept and validates the idea of a portable lighting system for the DC House. In addition, it was proven to work with the DC light bulb along with its dimming feature.

6.2: Future Considerations

There is still much to improve with the DC Portable Lighting System explained in this thesis. These improvements include wider input voltage range, universal charging circuit, battery selection, and better component selection.

The DC Light Bulb was originally designed to function with a very wide input voltage range of 24V-72V. However, the LTC3891 ratings of the Portable DC Light Bulb system reduce the input range to 24V-60V. To create a wider input range, a different buck converter with higher input ratings could replace the current LTC3891 circuit.

The charging circuit was programmed to charge NiMH batteries. However, there are various types of battery chemistries that are better in performance and smaller in size. The

LTC4011 is designed only for Nickel based batteries. It can be recommended to implement a charging circuit that is able to switch conveniently between multiple chemistry charge types. This feature would make the Portable DC Light Bulb system very universal and flexible for many applications. Other battery chemistries can also allow for smaller batteries for a smaller system.

The number of batteries can also affect the system's efficiency and performance. The proposed system is designed for 6 AA NiMH batteries, but is suitable for an 8 AA NiMH battery expansion with minor resistor changes. It can be suggested for more batteries in series to increase the battery voltage and decrease the discharging current. Lower discharging currents can extend battery and system life. Permitting cost, it can also be suggested to switch battery chemistry to lithium ion for better battery quality and efficiency.

Although the Portable DC Light Bulb operates at high efficiencies, it is not the final design of the system. Again, there are many ways to improve the system efficiency such as reconfiguring the circuit or selecting other converter topologies.

For example, a controller can be implemented to bypass the three sub-circuits and reduce power loss in each mode. The DC light bulb can be connected directly to the 48V input of the flashlight adaptor and can operate regardless of the charging state. If the battery requires the charging operation, it would utilize the Buck converter and the charging circuit. The controller would then disconnect the Boost converter and increase efficiency by omitting a converter from the active circuit. If the Portable DC Light Bulb was disconnected from the 48V DC bus, the controller could reconnect the Boost converter and the DC Light Bulb could draw power from the batteries. The Buck converter and charging circuit would be "off" due to the lack of a DC input.

Furthermore, a charging circuit with a higher DC input rating can benefit the system by allowing the Buck converter to be omitted. Less conversion stages or circuits will result in lower power losses and higher efficiencies.

Lastly, better component selection can also increase the system's efficiency. During hardware testing, the buck and boost converter inductors were very hot at higher currents and contribute to the low efficiencies.

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