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An Electrolytic Capacitor-Less Approach to Eliminating Flicker in LED Lighting

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AN ELECTROLYTIC CAPACITOR-LESS APPROACH TO ELIMINATING FLICKER IN LED LIGHTING

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering

By

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B.S., Wright State University, 2013

2016
Wright State University
January, 6 2015

WRIGHT STATE UNIVERSITY
GRADUATE SCHOOL

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Alex M. Kavouras ENTITLED An Electrolytic Capacitor-Less Approach to Eliminating Flicker in LED Lighting BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Electrical Engineering.

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ABSTRACT

Kavouras, Alex M. M.S.E.E. Department of Electrical Engineering, Wright State University, 2016. An Electrolytic Capacitor-Less Approach to Eliminating Flicker in LED Lighting.

In today’s lighting industry, there is a high demand for quality, long-lasting light bulbs. Light emitting diodes offer the means for long-life bulbs, while producing a quality output. The issue with the current state of solid-state lighting is how to drive LEDs and maintain their full potential. Many solutions offer either a long-life bulb or a high quality output. The trade-off for a long-lasting bulb typically comes with an output quality that is visibly or invisibly flickering. In order to effectively eliminate flicker from the output of the LED, a large output capacitor is needed. An electrolytic capacitor is a desirable choice because its capacitance can be quite large, while maintaining small package size. The drawback to electrolytic capacitors is their limited lifespan. By eliminating the limiting factor, the electrolytic output capacitor, from the driver, the LED can perform to its full potential lifetime. With the addition of a buck-boost topology in place of the electrolytic output capacitor, the flicker in the LED can be effectively eliminated, while maintaining a small package size. The result is a long-lasting, quality output LED driver.
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For my Wife
1. **Introduction**

1.1 **Overview**

This thesis discusses strategy for designing an LED driver which reduces the amount of flicker at the output. The issue at hand is that many of the LED driver options available today may contain some amount of visible or invisible flicker in the lighting output. The thesis will be presented such that section 2 will give a history of electric lighting; section 3 will discuss LED lighting and operation; section 4 will introduce flicker and discuss its effects; section 5 will discuss driver options and a proposed solution to solving the flicker problem. Section 5 will also discuss theoretical and experimental results and provide some future improvements to driver topology. Section 6 will conclude the document.

1.2 **Objective**

The objective of this work is to design and construct an LED driver utilizing an electrolytic capacitor-less methodology. The design process will be discussed, and then implemented through LTSpice simulation. After the simulation issues have been worked through, a working prototype will be built. The goal of the prototype will be to completely filter out given ripple signals and provide a clean, quality LED output.
2. **History of Electric Lighting**

2.1 **Early Lighting**

Electric lighting dates back to the early 1800s with the development of the carbon-arc lamp in England by Sir Humphrey Davy [1]. The carbon-arc lamp worked by creating an arc between two carbon rods made from charcoal. The resulting lamp was a very bright, high-output light. The arc was provided by batteries, which wasn’t very efficient, but provided the first stepping stone for electric lighting. By the mid-1800s, more practical electric generators were employed, which allowed for more widespread use of carbon-arc lamps. Another issue of practicality for the carbon-arc lamp was the fact that the carbon was consumed as the lamp burned, leading to frequent replacement of the charcoal rods [2]. Because the light from the carbon-arc lamp was so bright, there was a need for a lower output light for use indoors. Lower output lights would be smaller and require less current for power. Thomas Edison recognized this need, and from 1878-1879, he developed the incandescent light bulb [2]. In England, Joseph Swan developed a similar incandescent bulb. There was earlier development in the 1840s of the incandescent bulb by William Grove, who used platinum filaments, but Edison and Swan took the design further [1].

First introduced in 1880, the incandescent light bulb revolutionized lighting. Initially, Edison used a platinum filament in light bulbs because of its high melting point and very slow oxidation rate [2]. To keep the filament from overheating, Edison created a current shunt within the light bulb to regulate the output. This created the first flickering effect when the light bulb quite literally would shut off every few minutes. To
avoid this issue, Edison worked with different materials to use as a filament for his bulbs. Ultimately, he settled on carbon filaments sealed in a vacuum bulb. Power is provided at the base of the bulb and light is emitted from the heated filament. Along with the carbon-arc lamp, incandescent bulbs could be AC or DC. Edison’s original lamps were DC [2]. Eventually, a change to AC power was made because it was found to be more efficiently distributed over long distances.

2.2 Lighting Evolves

The incandescent bulb continuously evolved into the early 1900s. General Electric developed harder carbon materials for use as filaments, but it wasn’t until William Coolidge experimented with tungsten that a new material was used [1]. While tungsten is weaker than carbon, it has a higher melting point and can burn brighter. By 1920, tungsten was the standard for incandescent bulbs [1]. One caveat with the high temperature materials is evaporation, which causes the glass on the lamp to turn black. This can be overcome by filling the vacuum bulb with an inert glass, which reduces evaporation. In early trials, nitrogen was used to fill the bulbs, but was later replaced by argon because it has lower thermal conductivity [2]. Tungsten filaments are still used to this day, although the incandescent lamp is slowly being phased out of use. Even with the dominance of incandescent lighting, different lighting options were still be researched.

During the middle of the 20th Century, experimentation was being done with metal halide lighting. Although Steinmetz experimented with metal halides as early as 1912, the technology wasn’t really made useful until the 1950s [2]. Metal halide lamps
work by supplying a high starting voltage to mercury vapor to create a high intensity light. Salts inside the lamp are used to improve the quality of the output color. In the 1960s, Gilbert Reiling experimented with metal halide at General Electric. He worked with sodium and thallium and was able to improve on early mercury vapor models of the metal halide lamp [2]. The resulting lamps were higher efficiency and had better color. Metal halide is very high intensity, and therefore useful for outdoor lighting. Options for indoor lighting were broadened with the invention of the compact fluorescent bulb.

The idea of the fluorescent lamp is not a new one. The idea for the lamp dates back to the 1880s, while practical inventions, like the calcium tungstate lamp by Thomas Edison, came in 1896 [2]. The fluorescent bulb works by removing the air from a glass tube and replacing it with a gas such as mercury or phosphor [1]. A current is provided to the tube and light is emitted. Fluorescent bulbs are an extremely effective light source, still in use today. Since a large amount of space is required to for the energy to discharge, the tubes were typically long, making them impractical for standard home lighting. However, the development of the compact fluorescent light (CFL) made it more practical to bring this form of lighting into the home. Since a smaller more energy efficient lamp became available, the incandescent was effectively replaced [1]. The quality of light for fluorescents, while efficient, can be a bit cumbersome in a typical consumer setting. The bulbs need to warm up when turned on, resulting in a slow ramp up of the light output. Additionally, CFLs succumb to flicker quickly when dimmed, making them less desirable for many commercial applications, such as restaurant lighting. Similar to incandescent lamps, fluorescents are still widely in use today. However, as technology presses on, lighting continues to evolve.
2.3 Modern Lighting

At the forefront of today’s lighting industry is the light emitting diode (LED). Still in its infancy, solid-state lighting (SSL) provides an efficient and cost effective light source. While the demand for LED lighting is ramping up, the technology itself is not new. First developed in the 1960s, red LEDs were offered for commercial applications [3]. During the period from the 1970s through the mid-1990s, more colors were developed, but the output lighting was only a few lumens [3]. Since the output was not very bright, LEDs did not have many daily practical applications. However, around the turn of century, development of the LED and driver technology took off with the need to develop more energy efficient lighting. Today, LEDs are used in many markets from home lighting and electronics to industrial and aircraft applications.
3. **LED Operation**

3.1 **The Light Emitting Diode**

A light emitting diode, or LED, is a semiconductor device, which acts as a light source. In a forward-biased $p$-$n$ junction, free electrons in the $n$ side of the device cross the junction and recombine with holes on the $p$ side of the device [4]. In some diodes, such as silicon based, the energy released during recombination is released as heat. However, in other diodes, such as gallium arsenide and gallium phosphide, the energy released during recombination is released as light [4]. The $p$-$n$ junction of these diodes is what makes the LED. For a typical LED, the forward voltage $V_F$ is $2–3$V and $10–20$ mA of current. Fig. 1 illustrates the LED with terminals and symbol.

![LED with Terminals and LED Symbol](image)

**Fig. 1: LED with Terminals and LED Symbol**

Current flows from the anode to the cathode across the $p$-$n$ junction of the diode. Fig. 2 shows an LED biasing circuit with a series resistor.
Using Ohm’s Law, the current through the LED can be determined.

\[ I_{LED} = \frac{V_{dc} - V_F}{R} \]  

(1)

By equation 1, it can be seen that the intensity of the light from the LED is proportional to the forward current through the device. Using either a variable supply or a potentiometer with variable resistance, the forward current through the LED may be increased or decreased. Fig. 3 shows the changes in forward current versus the change in resistance or input voltage.
3.2 The LED Driver

In order to use an LED effectively, a proper driver must be employed. The driver is a power supply, which has an output ideal for powering an LED. The driver works such that an AC power supply powers the driver. The input is filtered and flows through a bridge rectifier to create a DC signal. The signal enters a DC-DC converter and outputs to the load. In this case, the load is the LED. The output capacitor filters the AC signal and allows the DC drive signal to flow through to the load. Fig. 4 shows a basic LED driver design.
Fig. 4: Basic LED Driver

The output wave forms for the driver can be seen in Fig. 5.

Fig. 5: Output Current of Basic Driver through LED (22µF 300mA ripple)

From Fig. 5, it can be seen that the output has a current ripple of 700 mA. The ripple creates an undesirable characteristic at the output of the circuit. In an LED, the output ripple results in a poor quality of lighting with a flicker effect.
4. **Flicker in LED Lighting**

4.1 **Definition of Flicker**

Flicker is defined as an unsteady lighting quality. In LED lighting, percent flicker is defined as a relative measure of the cyclic variation in output of a light source [5]. This can also be considered a percentage of modulation. Another measure used for flicker is the flicker index, which is a reliable relative measure of the cyclic variation in output of various sources at a given frequency [5]. Fig. 6 [5] shows an example of the flicker index. The flicker index is defined as the area above the line of average light divided by the total area of the light output curve for a single cycle [6].

![Flicker Index Diagram](image)

**Fig. 6: Flicker Index**

Flicker is associated with bad lighting quality and other drawbacks. In addition to being aesthetically displeasing, there are also health risks associated with flicker. These health risks include epileptic seizures, malaise, headaches, and impaired visual performance [7]. The risk of seizure comes from flicker in the 3Hz – 70Hz range, while the other risks typically occur from 70Hz – 165Hz [7]. The upper range is known as invisible flicker as it is not easily noticeable.
Flicker occurs when the interharmonics of a rectified signal affect the quality of the output [7]. Where incandescent lighting is produced directly from an AC signal, LEDs require a rectified DC signal to operate. This rectified signal produces interharmonics in the ranges of the 2\textsuperscript{nd}, 3\textsuperscript{rd}, and 5\textsuperscript{th} order harmonic [7]. The second harmonic will produce flicker that may be detectable to the human eye. However, the 3\textsuperscript{rd} and 5\textsuperscript{th} harmonics contribute to invisible flicker, which is also undesirable.

4.2 Reducing and Removing LED Flicker

Most LED drivers are able to filter out the higher order harmonics with the use of an output filter capacitor. However, in order to filter the 2\textsuperscript{nd} order harmonic, this capacitor needs to be quite large. The basic LED driver shown in Fig. 4 was simulated using 1000 \( \mu \)F and 47 mF capacitors to illustrate the refined output using a larger capacitor. The results can be seen in Fig. 7a and 7b.

![Fig. 7a: Output Current of Basic Driver through LED with 1000 \( \mu \)F Filter Capacitor](image-url)
In Fig. 7b, the capacitance of the filter capacitor is increased to 1000 \( \mu \)F which shows a decrease in the ripple from Fig. 5 to about 70 mA. However, the charge time for the capacitor increases to around 30 ms. In Fig. 5b the capacitance is increased to 47 mF. This results in a desirable output ripple of around 3 mA, but the charging time of the capacitor is around 1.5 s. In addition to the undesirable charge time, the 47 mF capacitor would most likely need to be an electrolytic type in order to maintain a small package suitable for an LED driver. As discussed later, the electrolytic capacitor is a limiting factor due to its relatively short lifespan in relation to other circuit components.
5. Electrolytic Capacitor-Less Approach to Removing Flicker in LED Lighting

5.1 Flicker Reduction through Power Factor Correction

There are options available to correct the problem of flicker in an LED, but as with many new technologies, these options come with their drawbacks. One of the biggest methods for controlling LED output in use today is achieved through power-factor correction (PFC).

Power-factor is the effectiveness of energy transmission from a source to a load [9]. With an AC signal, current harmonics may exist as a part of the power system. These harmonics degrade the signal, resulting in poor output power quality. In the case of LEDs, this is prevalent in the light quality resulting in flicker. In order to correct the power factor to create a desirable output, a large filter capacitor is added to the output of the rectifier in order to change the conduction angle of the diode and correct the power factor [9]. This works because the filter capacitor remains almost constantly charged at or near the peak ac voltage [9]. In order to further reduce the flicker in the LED, different PFC topologies have been introduced.

5.1.1 Passive PFC plus switching DC/DC converter

The first topology is a passive PFC plus switching DC/DC converter. This circuit works by first adding a passive filter to the output of the rectifier in the PFC followed by a switching DC/DC converter in the second stage [5]. This design fills the valley of the output current while the capacitors keep the output from sagging resulting in a low current ripple that is easy to control [5]. The drawback of this circuit topology is that it
does not provide a stable output above 20W and is not well suited for standard input voltage ranges of 100-240 VAC [5]. Therefore, using a standard US 110 VAC input would not be ideal for this circuit. The passive PFC topology can be seen in Fig. 8.

![Passive PFC Diagram](image)

**Fig. 8**: Passive PFC Stage plus a DC/DC Converter Stage LED Driver

### 5.1.2 Single-Stage Active PFC

The next possibility for correction is a single-stage active PFC circuit. This circuit is similar to the passive PFC plus DC/DC converter, but eliminates the passive stage and relies on an AC/DC converter. The passive stage is removed to provide higher output power capabilities as well as voltage inputs in the range of 100-240 VAC [5]. While the circuit is effective at eliminating visible ripple, the removal of the passive filter results in a high-frequency, invisible flicker in the 100-120 Hz range [5]. While this flicker is not noticeable to the human eye it can still have unwanted health side effects. Additionally, this circuit is highly dependent on the load provided by the LED, therefore it is difficult to have a standard design [5]. The single-stage active PFC topology can be seen in Fig. 9.
5.1.3 PFC with Ripple Suppressor

Building off of the single-stage topology, a ripple suppressor can be added to the circuit to further reduce the output current ripple. The circuit is modified such that a linear regulator is added to reduce the ripple from the single stage circuit with a minimal efficiency loss of around 2-3\% [5]. The ripple suppressor is used in series with the single-stage PFC and consists of a power MOSFET, a current sense resistor, and an error amplifier. If the ripple sensed by the resistor is higher than a given value, the error amplifier adjusts the output voltage across the MOSFET to reduce the ripple [5]. While some ripple still exists, this approach is both simple and cost effective. The ripple suppressor circuit can be seen in Fig. 10.

Fig. 9: Single-Stage Active LED Driver
5.1.4 Active PFC plus Switching DC/DC Converter

Another PFC topology to be considered is an active PFC stage plus a switching DC/DC converter. In this example, a DC/DC converter is added after the active filter, which greatly reduces the output ripple of the first stage [5]. While effective and practical for most power levels required for typical applications, the additional DC/DC converter adds an additional 15-20% on to the cost of the driver [5]. This topology is common in today’s LED drivers [5]. The Active PFC plus switching DC/DC converter topology can be seen in Fig. 11.
The advantages of power factor correction are clear; for many topologies the resulting output is a cleaner signal with a reduced ripple. However, PFC is not without drawbacks. These topologies may exhibit high frequency ripple, reduced power capability, and increased size and cost. PFC has earned its place in today’s industry, but there are other methods available to reduce flicker.

Another method for reducing flicker in LED lighting is through pulse-width modulation (PWM). PWM involves varying the duty cycle of a wave in order to control a dc output voltage [9]. In the case of driving an LED, the controlled DC output will deliver a constant driving current operating in continuous conduction mode (CCM). The basic concept is that the LED is duty cycle driven. This means that the LED is on while the given signal is high. At high frequencies, there is no apparent flicker for higher duty cycles. Because LEDs have an extremely fast response to a driving current, they are ideal for use with PWM [6]. At high-frequencies, most or all of the output ripple can be filtered out. However, when the LEDs are to be dimmed and the frequency is reduced, a flicker will be present at the output. Although some of the flicker may be filtered out,
there will still be invisible flicker present during low-frequency driving [6]. As stated, PWM is an ideal option for high frequency LED operation. When combined with a buck-boost topology as presented herein, an effective driver may be designed.

5.2 Electrolytic Capacitor-Less AC-DC LED Driver

The previously mentioned options offer different viable solutions to the flicker problem. However, there is a simpler approach which should be considered as a viable option for the LED driver. The limiting factor in the driver circuit is the electrolytic storage capacitor. This capacitor reduces flicker in the output of the LED. However, the typical lifespan of an electrolytic capacitor is around 5,000 hours, whereas the lifespan of a typical LED is around 50,000 hours [10],[13]. If the lamp runs below its maximum junction temperature, that life could be extended as high as 100,000-200,000 hours [3]. In order for the circuit to be the most cost-effective, it should be able to last as long as its main component, the LED. Over time, as the electrolytic capacitor breaks down, its ESR is increased, which in turn decreases its capacitance. Because the capacitor starts to break down after 5,000 hours of use, this output capacitor is estimated to have the highest rate of failure for all components in the driver [11]. The best option to increase the life of the LED driver is to remove the electrolytic output capacitor altogether, and replace it with a more robust alternative.

The electrolytic capacitor could be replaced with a capacitor utilizing a different dielectric type. However, these capacitors, such as a ceramic or tantalum type, would need to be quite large in order to provide the same capacitance as an electrolytic. In order
to remove the flicker and maintain a reasonably sized capacitor, the circuit will need to be modified to include some additional topology.

There are several methods for removing the electrolytic capacitor from the driver. The capacitor could be replaced with a magnetic energy storage component, but these can be quite large and cumbersome [10]. Another method would be to remove the pulsating component at the input, thereby reducing the input ripple and in turn, the output ripple [10]. By reducing the ripple at the input, the storage capacitor at the output could be reduced in size allowing for a different capacitor type to be used. Additionally, an active filter may be used to isolate the storage cap from the input and output terminals of the driver [10]. These methods all have issues regarding efficiency, circuit size, and cost. In order to remove the electrolytic capacitor in a cost and size effective manner, a different approach will be taken.

The topology focused on in this paper will be that of an electrolytic capacitor-less, single-phase AC/DC LED driver. The proposed topology will consist of an input rectifier, PFC converter and a buck/boost converter at the output capacitor, which will be used to remove the second harmonic ripple of the driver. A filter capacitor $C_o$ at the output of the PFC converter acts as a path for the switching harmonics. This is not the same electrolytic capacitor that would traditionally be seen at the output of the driver. Since this capacitor is only filtering small harmonics, it is therefore small and can be made from different material such as ceramic. An inductor $L_o$ at the output acts as a low-pass filter, which filters out harmonics preventing them from affecting the output quality of the LED. The block diagram of the driver can be seen in Fig. 12.
5.3 Driver Design

In determining the relevant parameters of the circuit, the following equations can be used.

The input voltage is defined as,

\[ v_{in}(t) = V_m \sin \omega t \]  \hspace{1cm} (2)

The input current is defined as,

\[ i_{in}(t) = I_m \sin \omega t \]  \hspace{1cm} (3)

where \( V_m \) and \( I_m \) are the amplitudes of the voltage and current respectively.

The angular frequency is defined as

\[ \omega = \frac{2\pi}{T_{line}} \]  \hspace{1cm} (4)
From the above equations (2) and (3), the instantaneous input power is determined to be.

\[ p_{in}(t) = P_{in}(1 - \cos 2\omega t) \]  

(5)

where

\[ P_{in} = \frac{V_m I_m}{2} \]  

(6)

Using the theory of an AC/DC converter, the AC current is filtered by \( C_o \). Therefore, the remaining small DC current passes though inductor \( L_o \). This effectively makes the voltage across \( L_o \) zero [9]. The result is an output voltage \( V_o \) equal to the voltage across \( C_o \). This is the constant DC voltage that drives the LEDs.

In an ideal configuration with no power losses, and a negligible storage capacitance the output power will be equivalent to the input power, \( p_o = p_{in} \) [10]. The resulting current is

\[ i_o'(t) = \frac{p_o}{V_o} - \frac{P_{in}}{V_o} (1 - \cos 2\omega t) \]  

(7)

It is clear from equation (7) that the output current contains a second harmonic ripple. This second harmonic must be controlled in order to remove the flicker from the LED. Using the proposed topology, a buck-boost converter is introduced to provide a path for the current flow of the second harmonic [10]. This is achieved by making \( i_b \) equal to the second harmonic [10]. The resulting current is
\begin{equation}
    i_b(t) = -\frac{P_{in}}{V_o} (\cos 2\omega t)
\end{equation}

By introducing \( i_b \), the output \( i'_o \) will effectively be cancelled resulting in a clean output current free of the second harmonic.

The resulting output current is defined as

\begin{equation}
    i_o(t) = i'_o(t) - i_b(t) = \frac{P_{in}}{V_o}
\end{equation}

Since the second harmonic is eliminated by equation (9), the resulting output is a DC current to drive the LED which will be free from flicker. Generic plots for these waveforms are shown in Fig. 13 [9].

Fig. 13: Voltage and Current Plots for LED Driver with Buck-Boost Converter
The electrolytic capacitor-less LED driver circuit can be seen in Fig. 14. The circuit shown was used for simulation as seen later in this section.

![Electrolytic Capacitor-Less LED Driver Circuit Diagram](image)

**Fig. 14: Electrolytic Capacitor-Less LED Driver Circuit**

Some modifications were made to the circuit compared to the model in [10], to account for parasitics in the circuit. The values for the representative parasitic resistors were chosen based on actual hardware after the component values were determined. A filter capacitor was also added to the output of the diode bridge to ensure a smooth simulation. Like [10] and [13], a flyback converter is used as a PFC converter operating in discontinuous conduction mode (DCM). Operation in DCM allows for a constant switching frequency, aiding in transformer design and preventing reverse recovery of the flyback diode [10].
In order to determine the component values in the circuit, the operating principles of the circuit, as given in [10], must first be understood. First the transformer current in the primary winding $i_p$ is determined such that,

$$i_{p-peak} = \frac{V_m|\sin \omega t|D_y}{L_pf_s} \tag{10}$$

and

$$i_{p-avg} = \frac{1}{2}i_{p-peak}D_y = \frac{V_m|\sin \omega t|D_y^2}{2L_pf_s} \tag{11}$$

In this instance, $D_y$ represents the duty cycle of the transistor and $f_s$ represents the switching frequency of the transistor. The primary inductance of the transformer is given as $L_p$.

The secondary current $i_s$ is determined by,

$$i_{s-peak} = ni_{p-peak} \tag{12}$$

where $n$ is the turns ratio of the inductors in the transformer. From transformer theory, the relationship of the transformer inductances to the turns ratio is expressed as,

$$\frac{L_p}{L_s} = n^2 \tag{13}$$

where $L_s$ is defined as the inductance of the secondary winding.
To determine the average current through the secondary winding, the duty cycle for the reset time of the secondary current is expressed as,

\[
D_r = \frac{L_s i_{s-peak}}{V_o T_s} = \frac{V_m |\sin \omega t| D_y}{n V_o} \tag{14}
\]

The secondary current is expressed as,

\[
i_{s-avg} = \frac{1}{2} i_{s-peak} D_r = \frac{V_m^2 D_y^2 \sin^2 \omega t}{2 V_o L_p f_s} \tag{15}
\]

The output filter is created by \(C_o\) and \(L_o\). This filter removes most of the high-frequency harmonics in the secondary current \(i_s\). The result is a DC current \(I_o\), and as mentioned above the second harmonic ripple. Because the output filter doesn’t remove the second harmonic ripple, \(i_o\) from (7) can be expressed as,

\[
i_o' = i_{s-avg} = \frac{V_m^2 D_y^2}{4 V_o L_p f_s} (1 - \cos 2\omega t) \tag{16}
\]

and

\[
I_o = \frac{V_m^2 D_y^2}{4 V_o L_p f_s} \tag{17}
\]

The input power is defined as,

\[
P_{in} = \frac{V_m^2 D_y^2}{4 L_p f_s} \tag{18}
\]
From this, the duty cycle of the flyback converter can be determined using the input power.

\[
D_y = \frac{2}{V_m} \sqrt{\frac{P_{in}L_p}{f_s}} \tag{19}
\]

From the above equations and using the values given in [10], the duty cycle was determined to be \(D_y = .40\). Using the given value \(f_s = 200\) KHz, the on time for the flyback converter is 2 \(\mu s\). These values were determined assuming an input voltage amplitude of \(V_m = 115\) V.

As given in [10], the primary inductance is \(L_p = 80\) \(\mu H\). For the transformer, given that \(n = 2\) and \(L_p = 80\) \(\mu H\), from (13) it can be determined that the inductance of the secondary winding is \(L_s = 20\) \(\mu H\).

The purpose of \(L_o\) and \(C_o\) is to filter out the high-frequency harmonics from the secondary current \(i_o\) [13]. In order to determine the values for these components, the attenuation ratio of the current harmonic must be looked at as shown in (20),

\[
\xi = \left| \frac{1}{1 - \omega^2 L_o C_o} \right| \tag{20}
\]

For the purpose of better attenuation, \(\xi\) should be as small as possible [13]. Using a value of \(\xi = 0.05\) @ 200 kHz results in the following equation,

\[
L_o C_o = 13.94 \times 10^{-12} \tag{21}
\]

Since all that is required is to meet the proper ratio as shown in (21), the components may be chosen to keep package size small. Choosing \(C_o = .47\) \(\mu F\), a small capacitor may be
used, avoiding the need for an electrolytic [13]. This results in a value of $L_o = 2.96 \, mH$ so $L_o = 30 \, mH$ was chosen.

For the buck-boost converter, the goal is to choose $L_b$ such that the inductor is able to quickly track the current reference [10]. This means that $L_b$ must be chosen properly in order for the current to quickly match the secondary current. This will allow the two currents to cancel out, resulting in little to no ripple on the output. The idea is that the line frequency in an ac source is 50 Hz, which gives a second-harmonic frequency of 100 Hz. In order to ensure that the tracking is not an issue, a frequency of 100 kHz is chosen for the buck-boost converter [10]. $L_b$ must also be chosen such that its inductor ripple current is small. The challenge in correctly choosing is that if the inductor is too small, the current ripple will be large; if the inductor is too large, it won’t be able to quickly track the current [10]. The inductor current ripple can be found by,

$$\Delta i_L = \frac{V_{Co}}{L_b} d_{Q1}(t) T_{s2}$$  \hspace{1cm} (22)

where,

$$L_b = \frac{(v_{cdc}(t) - V_{Co})V_{Co} T_{s2}}{V_{cdc}(t) \Delta i_L}$$  \hspace{1cm} (23)

$T_{s2}$ is the period of the switches in the converter and $d_{Q1}$ is the duty cycle of the switch $Q_1$. The duty cycle is given as,

$$d_{Q1}(t) = 1 - \frac{V_{Co}}{V_{cdc}(t)}$$  \hspace{1cm} (24)

The frequency of the buck-boost converter as given in [10] is $f_{s2} = 100 \, kHz$, giving $T_s = 10 \, \mu s$. The voltages used are $V_{Co} \approx 48V$ and $V_{cdc} = 85V$. The
determination for $V_{dc}$ is presented later. Substituting into (20)-(22) gives, the duty cycle of $d_{Q1} = 0.43$ and $L_b = 0.998 \text{ mH}$. A value of $L_b = 1.1 \text{ mH}$ was chosen. From the previous statement about choice of $L_b$, the value of the inductor isn’t as important in regards to current tracking because the bidirectional converter frequency was chosen to be 100 kHz. So the inductor is chosen such that it will result in a small current ripple. From the simulation of the circuit, it can be seen that there is negligible ripple on the buck-boost inductor current. The results are shown in Fig. 15.

![Fig. 15: Inductor Current $I_{Lb}$](image)

From the figure, it can be seen that there is a smooth inductor current. The current ripple is negligible at $i_b \approx 100 \mu\text{A}$. The current tracking capabilities will be evident in later figures.

To choose a value for $C_{dc}$, the minimum voltage of the capacitor must be determined. As given in [10],

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```
\[
\frac{1}{2} C_{dc} v_{dc}^2(t) - \frac{1}{2} C_{dc} V_{cmin}^2 = \frac{P_o}{\omega} \sin^2 \left( \omega t - \left( \frac{\pi}{4} \right) \right)
\]  

(25)

where,

\[
v_{c_{dc}}(t) = \sqrt{\frac{2P_o \sin^2 \left( \omega t - \left( \frac{\pi}{4} \right) \right)}{\omega C_{dc}}} + V_{c_{min}}^2
\]

and,

\[
V_{c_{max}} = \sqrt{\frac{2P_o}{\omega C_{dc}} + V_{c_{min}}^2}
\]

(26)

(27)

Additionally, the average voltage must be determined.

\[
V_{c_{dc}} = \frac{V_{c_{min}} + V_{c_{max}}}{2}
\]

(28)

In order to determine the proper value for \( C_{DC} \), equations (25) and (26) can be used. By plotting the equations with respect to the capacitor voltage and as a function of capacitance, the capacitor can be chosen using the plot in Fig. 16. As previously mentioned, the value for the minimum capacitor voltage is given as \( V_{c_{min}} = 48V \).
The capacitor is chosen such that the max voltage does not stress the switches $Q_1$ and $Q_2$ [10]. If a value of 20 µF is used, that gives a max voltage of $V_{C_{\text{max}}} = 115V$. This value will allow the voltage to be low enough to not stress the switches and also provide an average voltage, $V_{C_{\text{dc}}} = 82V$, which could be suitable for the use in a controller [10]. It is noted that $C_{\text{dc}}$ can be chosen to have a large second-harmonic, as it only appears at the output of the converter, not at the output of the driver [10].

Once the components were chosen, the design was verified through simulation using LTSpice. The results and analysis can be seen below in Fig. 17-19.
The ripple of the secondary output current $i_o'$ is minimal at 3 mA, but is highlighted to show that by equation (9), the output will have a minimal, negligible ripple. Using equation (9) and the values $i_b = 100 \, \mu A$ and $i_o' = 3 \, mA$, the output ripple can be predicted to be $i_o \approx 3 \, mA$. The output current is shown in Fig. 18 and 19. The dc output current is $I_O = 695 \, mA$. 

Fig. 17: Secondary Output Current Ripple $i_o'$

Fig. 18: Output Current $I_O$
The results show a successfully operating LED driver with no negative second-harmonic effects on the output.

For this simulation, the driver was built using real active components instead of ideal. Additionally, the parasitics of the passive components were also built into the simulation. This was done because there were issues running with ideal components, but this also allowed the simulation to show the full effect of how the driver would react at the output. The active components chosen are listed herein. The bridge rectifier comprises four diodes (RR2L6S), which are suitable to rectify 115 VAC. The flyback converter Q₃ is Si4848DY. The switches Q₁ and Q₂ in the buck-boost converter are STN3N45K3.

**5.4 Experimental Results**

The experiment conducted was run in accordance with the simulation discussed in section B. In order to build the circuit and ensure correct operation a few of the chosen components were changed from those in the simulation, other components remained the
same. The switches Q_1 and Q_2 in the buck-boost converter are STN3N45K3. The inductor L_o is 33 µH 7443551331 and the inductor L_b is 1 mH AIRD-02-102K. The capacitor C_{DC} is 22 µF CL31A226KAHNNE and the capacitor C_o is C3216X5R1E476M160AC.

The experiment was set up by building two circuits for comparison. The first was the basic LED driver as shown in Fig. 4. The second circuit is the LED driver with buck-boost converter as shown in Fig. 14. Each circuit was built with the idea that a DC signal would be provided to the driver and an AC signal would be injected at the input as a source of noise interference. The decision was made to take this approach as a controlled method for introducing flicker and to reduce the need for a full 115 VAC source in the lab setting, which could introduce safety issues. The output current across the LEDs is measured and the results compared to ensure the circuit is functioning as intended.

The conditions for the experiment were setup to closely match those in the simulations even without using an AC source. A 3.25 VDC voltage was applied to the input of both circuits. For the buck-boost converter switches Q_1 and Q_2, a 5V square wave was applied at a frequency of 100 kHz and 41% duty cycle. Without any additional signals present, both circuits show no ripple at the output across the LED. For the first case in the experiment, a 7 VAC @ 200 kHz signal was injected at the input of both circuits. Taking current measurements across the LEDs showed no ripple at the output of the driver with the buck-boost converter, while the other driver had a 113 mA ripple present at the output. In this case, the ripple is at 200 kHz so it is not visible to the human eye. For this reason, a second case of the experiment was conducted in which a 7
VAC @ 10 Hz signal was injected that would be visible at the output. The signal was applied to the input of both circuits. Again, the ripple was completely filtered out of the driver with the buck-boost topology, while the other driver had a 111 mA ripple present at the output. As expected, with the low frequency of the signal, the ripple is visible on the driver without the buck-boost converter. The results of experiment can be seen below in Fig. 20-23.

![Waveform](image)

**Fig. 20**: LED Output without Filter (7V @ 200 kHz Signal)
Fig. 21: LED Output without Filter (7V @ 10 Hz Signal)

Fig. 22: LED Output with Filter (7V @ 200 kHz Signal)
When compared with the theoretical results, the prototype performed better than the simulation. For the simulation, the output had a negligible, but existent 3 mA ripple on the output, which validated the design. The prototype had no ripple on the output, verifying a successful design.

There are several reasons why the experimental results varied from those in the simulation. First, the simulation required that specific components be chosen. The reason for this is that there were issues running the simulation with ideal components. The circuit would not operate properly. For this reason, components were provided with parasitic values from a restricted library within the simulator. The components used on the prototype were close to those in the simulation, but did contain some variance in the parasitic values. Another reason for the variation is that the input noise for the prototype was controlled in order to provide a safe operating environment. This meant that the input noise in the simulation varied slightly from that in the prototype.
The experiment shows that the addition of the buck-boost converter to the LED driver provides a viable filtration option to remove all ripple current across the LED. While the components used for this experiment had somewhat large packages for the purpose of prototyping and demonstration, it could be easily packaged into a small circuit.

5.5 Further Driver Improvements

While the design presented is effective, it presents a driver with extra components compared to a typical driver. In order to provide the necessary signals for driving the input power, the buck-boost converter, and the flyback converter, an additional controller should be added. The addition of a controller means more space taken up by the full driver topology.

To improve the design, a few approaches could be taken. First, utilizing very small components would aid in reducing the size of the overall driver with a controller. However, very small package sizes often come with increased costs. Another option would be to possibly reintroduce an electrolytic type capacitor with a specially designed heatsink for minimizing any extra heat on the capacitor. The lifespan of electrolytic capacitors is decreased heavily by high temperatures. A large heat sink could cool the capacitor, thereby extending its life. In either case, work remains to be done to make this driver both highly effective and in a desirable package size.
The next steps in this thesis may be carried over to a Ph. D. dissertation for further exploration into how to reduce the overall number of components in the driver as well as developing a fully functional prototype in a realistic package.
6. **Contribution to LED Lighting**

   LED lighting is the foremost technology in the artificial lighting market. From home illumination to commercial and industrial lighting, LEDs illuminate everything people use in their everyday lives. Lamps, appliances, flash lights, ballast lighting, emergency lights, and multitude personal devices all utilize LEDs for illumination. With everything that requires artificial light, it is important to provide an efficient, quality output. The importance of this lies within the benefits to both health and aesthetics.

   The LED driver presented in this paper sought to remove the flicker from the output of an LED. The results were a successful driver design that removed virtually all ripple current from the output. This design not only verifies existing an existing design, but changes were made to increase the capacitance of the output capacitor, while maintaining a small size. This design can be utilized in any application where LEDs are required. It can be used for the LEDs in the screens of devices such as cell phones, computers, and televisions where the quality of light is important due to the amount of time people spend staring at them. The lighting in an operating room requires that surgeons are able to see well and are not hampered by the dizzying flicker of poor quality lighting. By using the proposed driver in their lighting, hospitals can count on an excellent source of light for both doctors and patients. There are numerous other applications where this driver will be effective, so examining the design further and reducing package size will be very beneficial.
7. Conclusion

LED lighting is quickly becoming the new standard in home and commercial illumination. This lighting is low-cost, energy-efficient, and provides quality light. Unlike its in-home predecessor, incandescent lighting, LEDs are driven by a DC current. Because of this, drivers need to be designed to rectify a typical power outlet 90-264 VAC signal and filter out any undesirable current ripple. The output current ripple on an LED comes in both visible and invisible forms known as flicker. Flicker that is visible provides an undesirable strobing effect, which results in poor lighting quality and can have negative health effects. Flicker that is not visible occurs at high frequencies and is not apparent to the naked eye. However, this high-frequency flicker still has negative effects on health, such as headaches or even seizures in extreme cases. High-frequency flick can also affect one’s ability to concentrate, which is not ideal in a work setting. Low-frequency flicker is easy to filter out with most standard drivers available today. The issue in today’s drivers comes with high-frequency flicker. There are many ways presented in this paper to remove the flicker, but this often comes at the expense of cost, lighting quality, and/or driver package size.

An effective way to remove the high-frequency flicker at the output of the LED is presented in this paper. The limiting factor in the LED driver presented is the electrolytic filter capacitor at the output. While this capacitor is effective because it can have a large capacitance while maintaining a small package size, it has a short lifespan of around 5000 hours. Good design practices dictate that a driver be designed such that its lifetime is limited by the lifespan of its main component. In this case, the main component is the
LED, which can have a lifetime ranging from 50,000 to 100,000 hours depending on operating temperature. By designing an electrolytic capacitor-less driver with buck-boost topology, the life-limiting capacitor may be removed from the driver. The buck-boost converter utilizes a small capacitor whose capacitance is amplified to the output of the driver to effectively remove the current ripple at the output. The converter serves to remove the second-harmonic from the output, while a small filter cap at the output of the transformer is used to filter out higher-order harmonics. The result is a clean LED output with negligible current ripple.

Both the simulation and the follow-on experiment prove the effectiveness of the presented circuit. The prototype, while bulky, can be made smaller by reducing the size of components used. The trade-off for size does come at an increase to cost so other options can be looked at to improve this circuit. While this is an effective method for removing flicker from LED lighting, next-generation lighting will seek to further improve LED drivers.
**References**


Appendix A.

MATLAB Code

clear all
close all

VDC = 20;
VDC2 = 2:0.1:20;
VF = 2;
R = 1:0.1:10000;
R2 = 1000;

I = (VDC - VF)./R;
I2 = (VDC2 - VF)/R2;

subplot(1,2,1)
semilogx(R,I)
title('LED Forward Current vs. Change in Resistance')
xlabel('{$\nu R (\Omega)$}')
ylabel('{$\nu I_{L_E_D} (mA)$}')

subplot(1,2,2)
semilogx(VDC2,I2)
title('LED Forward Current vs. Change in Input Voltage')
xlabel('{$\nu V_d_c (V)$}')
ylabel('{$\nu I_{L_E_D} (A)$}')

Po = 35; %Output Power
VCmin = 48; %Min Cdc voltage
w = 2*pi*50;

Cdc = (1:0.001:100)/1000000; %Value of Cdc

VCmax = sqrt(((2*Po)./(w.*Cdc)) + VCmin.^2); %Max Cdc voltage
VCdc = (VCmin + VCmax)/2; %Average Cdc voltage

semilogx(Cdc,VCdc)
hold on
semilogx(Cdc,VCmax)
title('Capacitor Voltages vs. C_d_c')
xlabel('{$\nu C_d_c (F)$}')
xlabel('\text{it V}_\text{C\_d\_c} (V)')
legend('V\_C\_d\_c','V\_C\_m\_a\_x')
grid on