A thesis on

Studies on Tapped Inductor Converter as an Alternative LED Driver Topology

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Master of Technology
In
Illumination Technology and Design

Submitted by

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DECLARATION

I, Syed Sarim Hassan hereby declare that the thesis entitled “**Studies on Tapped Inductor Converter as an Alternative LED Driver Topology",** submitted as a part of my Master of Technology in Illumination Technology and Design is entirely the result of my work and my effort. I have not already obtained any other degree or diploma in my name from Jadavpur University or any other university or college based on this work. I declare that I understood the concept of plagiarism and this thesis has been carried out by me without resorting to plagiarism.

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Abbreviations

Code	Full form and Meaning
IEC	International Electrotechnical Commission
CrCM	Critical Conduction Mode
ZVS	Zero Voltage Switching
LED	Light Emitting Diode
WIEO	Wide Input Extreme Output
COB	Chip on Board
PQ	Power Quality
THD	Total Harmonic Distortion
V	voltage
A	ampere
W	watt
OCP	Overcurrent Protection
OVP	Overvoltage protection
SCP	Short Circuit Protection
PWM	Pulse Width Modulation
NTC	Negative Temperature Coefficient
DC	Direct Current
AC	Alternating current
DPF	Displacement Power factor
MOSFET	Metallic Oxide Silicon Field Effect Transistor
CV	Constant Voltage
CC	Constant Current
CCT	Correlated Color Temperature
SCR	Silicon Controlled Rectifier
PCB	Printed Circuit Board

Introduction

The Light Emitting Diode (LED) is the most energy-efficient and expeditiously growing lighting technology. LEDs are designed to operate on low voltage DC electricity. However, most places supply high voltage AC electricity. The main function of the LED driver is to convert higher voltage, alternating current to low voltage, and direct current.

It also protects LEDs from voltage and current fluctuations. A change in voltage causes a change in the current supplied to the LEDs. In LEDs, the light output is proportional to the supplied current hence fluctuations in current can cause variable light output. If the supplied current becomes greater than the rated current then the temperature of the LED may rise and cause faster degradation. The LED lighting applications should employ drivers with high energy efficiency and comply with the International Electrotechnical Commission (IEC) [Gacio and others 2011] mandatory regulations in terms of harmonic content and power-factor improvement.

According to data, Lighting loads in US commercial buildings make up for one-third of the building energy use whereas Residential buildings use 10-15%. So, when deciding which lighting products to use, looking at the efficiency of the products become important. The efficiency and power quality of the LEDs can be improved by using the appropriate LED drivers. The traditional LED drivers working at extremely low or high voltage lose efficiency and power quality.

The traditional LED drivers employ a Flyback converter topology to function. The drivers although having several benefits can only manage a maximum efficiency of around 90%. [Tanzamni and others 2017]. It shows poor performance at high power applications. Thus, further research needs to be done to achieve better efficiency and power quality by employing other driver topologies.

This project report deals with an alternative topology called the Tapped Inductor driver topology. MATLAB Simulations have been performed with LED load being driven by the traditional topology as well as Tapped Inductor topology. Various parameters have been measured and compared for both topologies to determine if the new alternative topology can be a replacement for the traditional topology.

Chapter 1 deals with general discussions on the light generation principles in LED. It consists of a discussion on the various components that a light system requires to function properly. Working principles of LED drivers have been discussed in this chapter. Flyback Driver and Tapped Inductor have also been discussed in this chapter.

Chapter 2 deals with the various parameters of LED drivers which determines if a driver is economically viable for use. Parameters like efficiency, power factor and total harmonic distortion, percent flicker, cost, constant current operation, and protection features have been discussed in this chapter.

Chapter 3 deals with the overall design of the LED drivers. It describes the specification of LED chips used. The configurations and linear model of the LED module have also been discussed. Calculations of both Flyback converter and Tapped Inductor topology parameters have been done in this chapter.

Chapter 4 deals with the Simulink Implementation and Evaluation of the driver topologies. Comparative analysis based on the various figure of merits has been performed to study the benefits and disadvantages of both the topologies.

Chapter 5 deals with observation and the future scope of the work on this topic.

Literature Review

In this modern age of energy crisis efficient lighting design for indoor and outdoor applications; users' requirement is very important. Besides this factor, another main concern is how the lighting design scheme will be effective from an energy point of view and the power quality of the distribution system. To keep the energy consumption by the system to a low level and to maintain the power quality of the distribution system to an acceptable limit, the main concerns are the types of lamps and control gears selected for the lighting installation. After the introduction of Light Emitting Diode (LED) in the market, it has become a promising alternative to other types of lamps.

LED drivers serve two main purposes, one is to convert higher voltage, alternating current to low voltage, direct current, and the other is to keep the voltage or current flowing through the circuit at its rated level. For the LEDs to be energy efficient the drivers need to be efficient as well. The driver should be such that it reduces energy losses and improves the power quality. So, a LED driver with improved energy-saving capability becomes somewhat mandatory.

A boost PFC converter offers high input to output voltage conversion with a nearly unity duty cycle but efficiency reduces with high-voltage gain using a high-duty ratio. Similarly, for a buck converter, efficiency is poor for very low voltage gain when the duty cycle is incredibly small. The poor efficiency is since the energy stored in the magnetic components is not effectively processed under such utmost value of high- or low-duty cycles. As a result, a high-pulsating current is generated, which increases the stresses on the semiconductor devices [Park and others 2007]. This can be undone by using Flyback converter-based LED drivers. The traditional Flyback drivers support both high step-up and step-down ratios as required in the HB-LEDs. However, the driver exhibits poor efficiency in high-power applications. A maximum of 90% converter efficiency can be achieved with the driver. [Tarzamni and others 2017].

Previous studies [Lamar and others 2012; Somnath and others 2020] show that introducing a transformer helps to attain a high-step-up or step-down conversion ratio by adjusting its turns to keep a reasonable duty cycle without giving up efficiency. For non-isolated converters, this transformer is named an autotransformer or simply a tapped-inductor. The primary concern of having lower electrical efficiency in conventional buck-boost converters was arrested due to the operation with exceptionally low and high duty ratios for the buck and boost modes, respectively. With the help of tapped inductors, the duty cycles were improved from 0.051 to 0.4 for buck operation and from 0.833 to 0.6 for boost mode of operation for the same voltage gain. The maximum efficiency achieved with a tapped version was over 95% whereas it was 92.5 and 93.5% for the buck and boost modes of untapped versions.

Research Gap Identified

Chips on board (COB) LEDs are one of the recent trends increasingly common in street lights, floodlighting, stadiums, and other outdoor areas. These are referred to as high-power LED lighting applications. COB types of LEDs are considered to be capable of working with high current and low-DC voltage. High brightness LEDs (HB-LEDs) offer very high lumen in compact chip size. HB-LEDs offer a wide range of voltage and current combinations. Various series and parallel combinations can be used to achieve desired power levels. These combinations often demand very high current, low-voltage DC drivers and vice versa. The buck, boost, and buck-boost converters cannot perform satisfactorily in such cases. Although the flyback converter can support high step-up and step-down ratios as required in the aforementioned HB-LEDs, the converter exhibits poor efficiency in high-power applications.

It can be said that the traditional LED drivers while driving LEDs in exceedingly low- or high-voltage levels lose their efficiency and power quality (PQ) performances as per IEC 61000-3-2. Therefore, a converter with improved energy-saving characteristics in extreme output (EO) conditions is indispensable in high-power LED lighting design.

Moreover, the cost of LED drivers is driven by the cost of individual components required in manufacturing. If the value of individual components is reduced their cost price reduces and so does the price of the driver. It becomes more affordable for the general public to switch to LED lights. It becomes a low-cost alternative to the available LED drivers. In this paper, such an LED driver topology has been evaluated and researched.

Objective

The aim of this paper is to assess Tapped inductor topology as a replacement for the flyback driver topology. Based on five important parameters , viz Efficiency, Power Factor, Total Harmonic Distortion, Percent Flicker and Cost the assessment is to be carried out.

Steps of Execution

1. A 60W LED load using the various series-parallel combination is designed.
2. Values of various internal components of both Flyback Driver as well as Tapped Inductor driver for a lighting load of 60W are calculated.
3. Both LED driver topologies are simulated in MATLAB Simulink.
4. Current and voltage waveforms of 60W LED module when driven by the LED drivers of different topologies at 230V,50 Hz supply at different dimming levels are recorded.
5. Efficiency, power factor, percent flicker, and total harmonic distortion at different dimming levels for both the topologies are calculated.
6. The recorded parameters are compared for both the topologies.
7. Depending on the results, the viability of tapped inductor LED driver as a replacement for the Flyback LED driver is determined.

Chapter One

LED Lighting System: Basic Principles and Components

This Chapter deals with the general discussion on the light generation principles in LED. It consists of a discussion on the various components that a light system requires to function properly. Working principles of LED drivers have also been discussed in this chapter. Emphasis has been given to the working principle of both the Flyback LED driver and Tapped Inductor driver.

1.1 Light Generation Principles in LED

Light-emitting diodes (LED) are a widely used standard source of light in lighting equipment. The LEDs are heavily doped p-n junctions. When the LED is forward biased the minority carriers(electrons) of the p- region are sent to the n-region and the minority carriers(holes) of the n-region are sent to the p-region. As a result, the concentration of minority carriers increases at the junction.The injected carriers recombine, and the energy difference before and after recombination is released as light. The emitted light depends on the energy band gap (E_g) of the semiconductor compound. The energy is released in the form of photons. This phenomenon is known as Electroluminescence. It is an optical as well as an electrical phenomenon in which materials emit light in response to the electric current passing through it. As the forward bias voltage is increased the intensity of the light also increases.

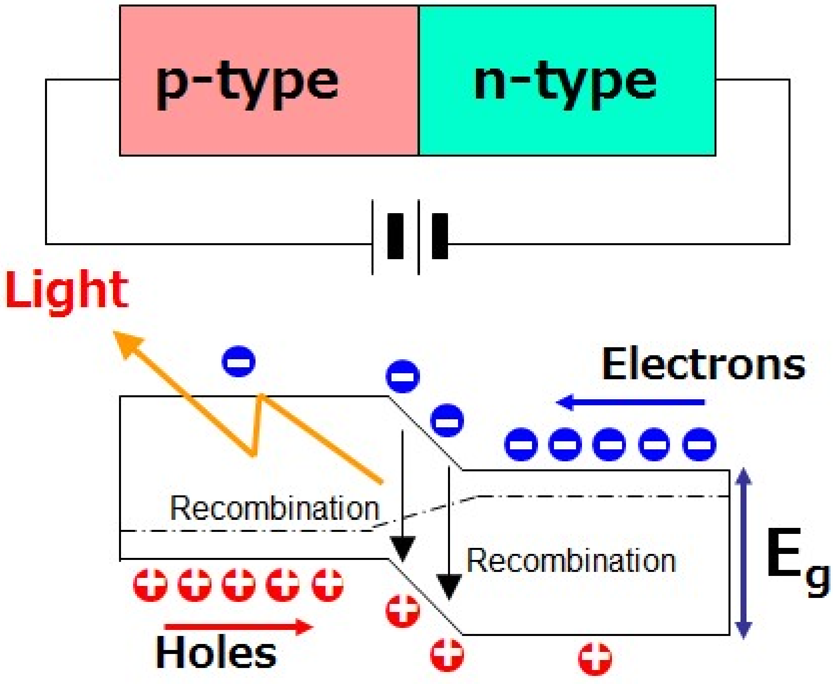


Fig 1.1: Mechanism of Light Generation- A schematic view

The color of an LED is determined by the semiconductor material in use. Aluminum gallium indium phosphide alloys and indium gallium nitride alloys are commonly used. Aluminum alloys are used to obtain red, orange, and yellow light, and indium alloys are used to get green, blue, and white light. Even the slightest of changes in the composition of these alloys change the color of the emitted light.

1.2 Components of LED Lighting System

There are four main parts of a LED Lamp:

1. LED chip: This is responsible for producing light when an electric current pass through it. It is made up of semiconductor material like aluminum gallium indium phosphide alloys and indium gallium nitride and depending on the material produces a different color of light. These are connected in various series-parallel combinations to get the desired illumination levels.

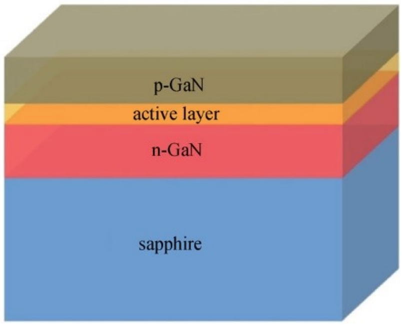


Fig 1.2: Schematic diagram of a LED chip

2. LED driver: It regulates the current flowing through the LED, similar to a ballast in a compact fluorescent light. LED drivers can be internal or external. LED Light output is proportional to its current and any slight variation in the current can result in unacceptable changes in light output. So, the led driver is a key component of the light output and greatly impacts the lamp life of the LED.

3. Heat sink: LEDs generate internal heat within the junction, High temperatures near the LED junction affect the short-term and long-term life and affect the LED performance. Heat must be removed from the LED Chip to maintain its light output, life, and color. Short terms effects of improper heat sinking include lower light output, and also a wavelength color shift, while the long-term effects include a lower lamp life. The heat sink is essential for removing heat which is removed through convection (by air) or by conduction (by contact). Aluminium is the ubiquitous choice of material for LED heat sinks.

Fig 1.3: Aluminium heat sink for LED lamp

4. Optics: It is also an important component of an LED lamp, which has multi-level optics. The Primary Optics is built directly on top of the LED chip. The Secondary Optic collects and redistributes the light in the LED lamp.

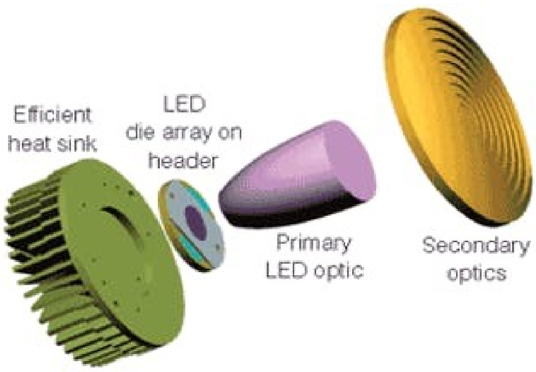


Fig 1.4: Components of a LED lighting system

1.3 LED Driver

A LED driver is an electronic device that regulates the power of an LED or a string (or strings) of LEDs.In contrast to conventional light sources that run directly from an alternating current (AC) power supply, LEDs operate on DC input or modulated square wave input because the diodes have polarity. An input of the AC signal will cause an LED to only light up approximately half of the time when the AC signal is at the correct polarity and immediately go out under negative bias. Hence, a constant supply of DC electrical current at a fixed output or a variable output within an allowed range must be applied to an LED array for stable, non-flickering lighting.LED drivers convert the incoming 50 Hz or 60 Hz AC line power to the regulated DC output current.An LED driver circuit should have immunity against voltage spikes and other noise on the AC line within a predetermined design range while also filtering out harmonics in the output current to prevent them from affecting the output quality of the LED light source. The driver is not just a power converter, LED drivers to have additional electronics to enable precise control of the light output or to support smart lighting.

Fig 1.5: LED Driver

The LED driver can be of different types:

1. Internal LED driver: These are commonly used in domestic LED bulbs to make it easy when replacing the bulbs; the internal drivers are usually housed in the same case as the LEDs.

2. External LED driver: The external drivers are housed separately from the LEDs and are usually used for outdoor, commercial, and roadways lighting applications.

Fig 1.6: Internal and External LED drivers

Depending on the operation LED drivers can be of 2 types:

1. Constant current LED driver: Constant current LED drivers to provide a constant current independent of the voltage load, to an LED module within a specific voltage range.Constant current LED drivers are used when the light output should be independent of the input voltage fluctuation. Constant current drivers support both pulse-width modulation (PWM) and constant-current reduction (CCR) dimming. Operating a power supply in a constant current mode usually requires overvoltage protection just in case an excessive load resistance is encountered or when the load is disconnected.

2. Constant voltage LED driver: Constant voltage LED drivers are designed to operate LED modules at a fixed voltage.Each LED module has its own linear or switching current regulator to limit the current to maintain a constant output.CV drivers are used in low voltage LED lighting applications.Constant voltage drivers can only be dimmed PWM .

1.3.1 Flyback Driver: Traditional Topology

The flyback driver is based on the buck-boost converter principle. A flyback driver utilizes a single high-voltage switching MOSFET and coupled inductor to provide energy storage and transfer to an isolated secondary and single-diode rectifying output circuit.When the MOSFET is switched on, the current in the primary of the coupled inductor rises linearly. During this phase, a magnetic field builds up in the air gap in the centre of the ferrite cores.When the MOSFET is switched off, the magnetic field collapses as its stored energy transfers to the load through the rectifier diode.

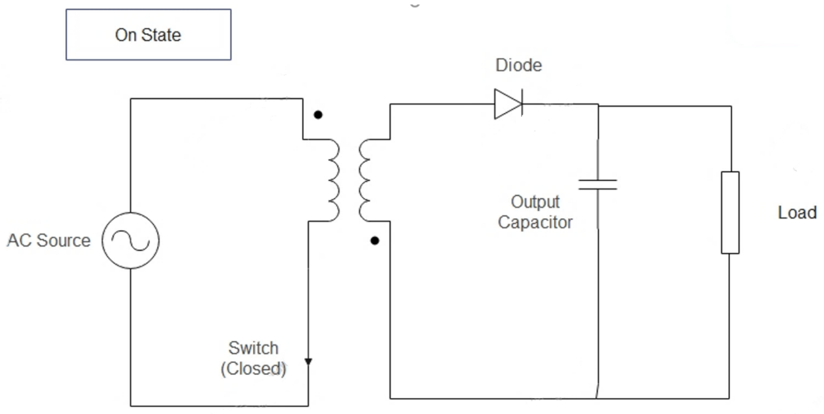


Fig 1.7: Flyback driver ON state

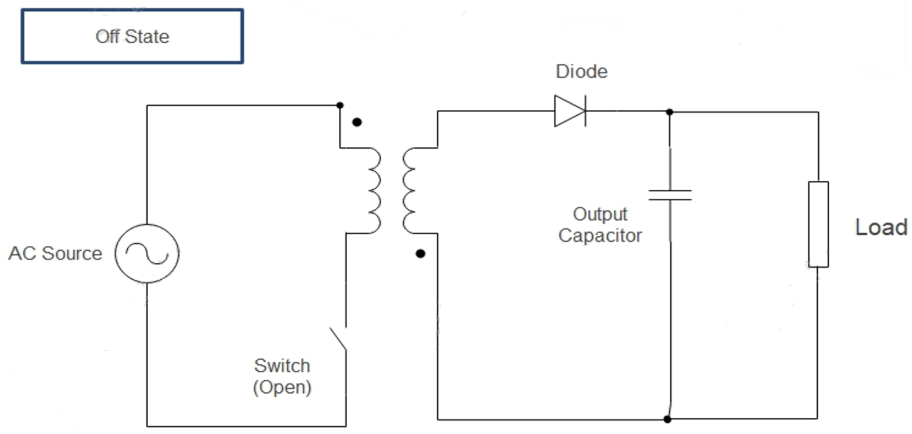


Fig 1.8: Flyback driver OFF state

The voltage at the inductor secondary rises to the desired level for current to flow and permit energy transfer. The output capacitor is used to reduce ripples in the output.The pulse width of the MOSFET gate drive signal determines the amount of energy stored per switching cycle and is controlled by employing an error amplifier that compares the LED current with a reference and either increase or decreases the pulse width to regulate energy transfer.Flyback LED drivers operate in critical conduction or transition mode (Which means that itbegins immediately after all of the energy stored in the inductor has been transferred to the output) to realize the advantages of quasi-resonant switching.

1.3.2 Tapped Inductor Driver: The New Alternative

A tapped inductor converter is a non-isolated converter. It can achieve high step-up and step-down ratios by adjusting the number of turns to keep a reasonable duty cycle without sacrificing efficiency. When working as a step-up converter, the tapped inductor can optimize the converter's output characteristics and higher output voltage. When it is used as a step-down circuit, its output characteristics can be optimized by using the diode-tapped inductor and lower output voltage. The primary advantage is that it supports both the functionality of buck and boost topologies.

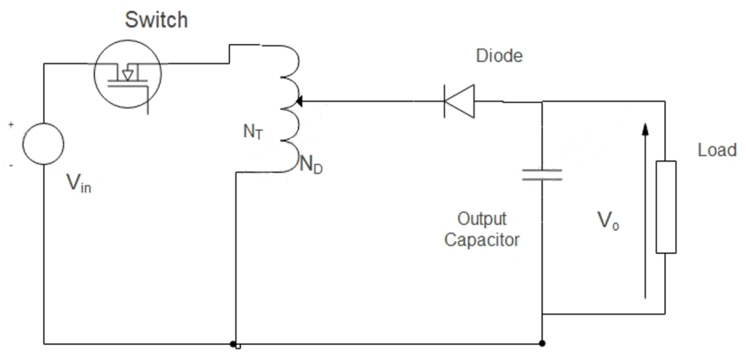


Fig 1.9: Tapped Inductor Driver

When the switch T is turned on, the power source V_{in}, switch T and tapped-inductor form a closed loop, and diode D is reverse biased. (as shown in Fig 1.10) In this condition, the turns of the primary side winding are N_T and inductance is $L_1=k(N_T)^2$, where k is a constant and reciprocal of magnetic reluctance. The voltage equation is given as (1.1):

$$V_{in} = N_T(\frac{d\Phi}{dt}) \quad (1.1)$$

Where Φ is the magnetic flux of the core of the tapped inductor. At the end of on state, the magnetic flux is increased by (1.2)

$$\Phi_{on} = T_{on}(\frac{V_{in}}{N_T}) \quad (1.2)$$

Where T_{on} is the time duration of on state in the switching cycle. The mmf obtained is given by the equation (1.3):

$$M = \Phi \times R \quad (1.3)$$

Where R is the magnetic reluctance of the tapped inductor core.
Thus, the mmf of the diode tapped inductor buck-boost driver during on-state M_{on} can be written as (1.4):

$$M_{on} = N_T \times (\frac{V_{in}}{L_1}) \times T_{on} \quad (1.4)$$

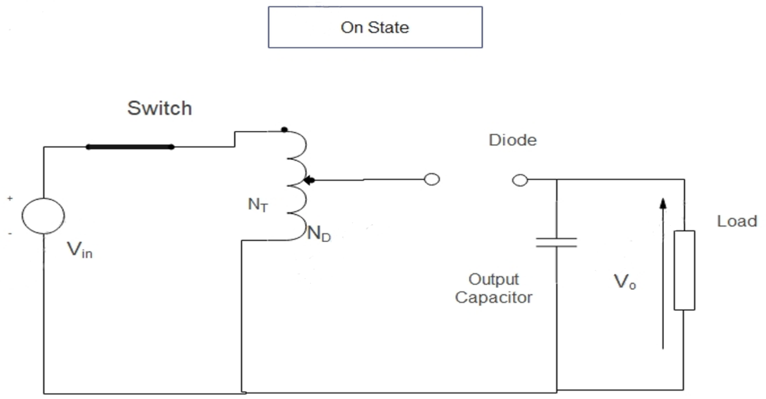


Fig 1.10: Tapped Inductor Driver Switch ON state

When the switch T is turned off, diode D is forward biased and forms a closed loop together with output capacitor C_O and tapped-inductor. (as shown in figure 1.11). In this condition, the turns of the secondary side winding are N_D and inductance is $L_2=k(N_D)^2$. The voltage equation is given by (1.5):

$$-V_o = N_D \times (\frac{d\Phi}{dt}) \quad (1.5)$$

At the end of switching off state the magnetic flux is given by equation (1.6):

$$\Phi_{off} = -T_{off}(\frac{V_o}{N_D}) \quad (1.6)$$

Where T_{off} is the total time in the off state. The mmf of the diode tapped inductor buck-boost driver during off-state M_{off} can be written as (1.7):

$$M_{off} = N_D \times (\frac{V_o}{L_2}) \times T_{off} \quad (1.7)$$

When the circuit is stable in operation, ΔM_{off} should equal to ΔM_{on}. Therefore, the voltage conversion ratio of the transistor-diode-tapped inductor Buck-Boost converter can be derived as (1.8):

$$\frac{V_{out}}{V_{in}} = -(\frac{N_D \times T_{on}}{N_T \times T_{off}}) \quad (1.8)$$

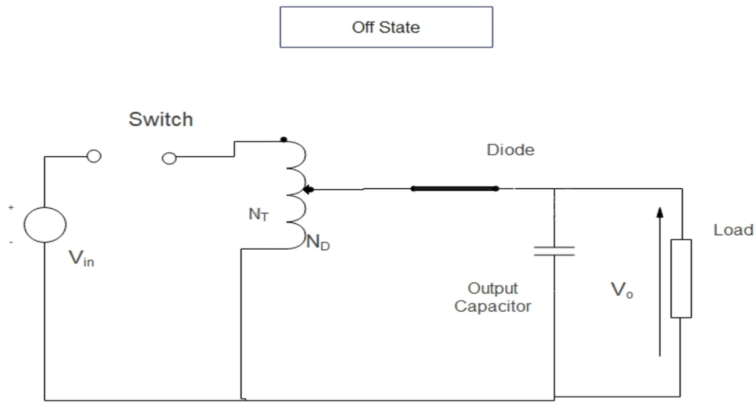


Fig 1.11: Tapped Inductor Driver OFF state

Chapter Two

LED Driver: Figure of Merits

This chapter deals with the various parameters of LED drivers which determines if a driver is economically viable for use. Parameters like efficiency, power factor and total harmonic distortion, percent flicker, cost, constant current operation, and protection features have been discussed in this chapter.

To determine whether Tapped Inductor driver is a better low-cost alternative to the Flyback converter some parameters are to be compared. Depending on the comparative analysis of the parameters it can be determined whether Tapped Inductor topology is a worthy replacement for the traditional Flyback topology.
The figure of merits the new alternative topology must outperform or perform at the same level as the traditional driver are as follows:

1. Efficiency
2. Power Factor and Total Harmonic Distortion (THD)
3. Percent Flicker
4. Constant Current Operation
5. Protection Features
6. Cost

2.1 Efficiency

The efficiency of the LED driver is given by the ratio of energy emitted by the driver to the power it consumes from the electric line. The LED driver contains many active and passive components. The active components include a transistor, integrated circuit, SCR, MOSFET, etc. Active components need power for their operation They can produce power gain and amplify signals. Due to the existence of parasitic resistance of the components like PCB, and cable, there is power loss occurring on the path through which the current goes.
Unlike active components, passive components are those part of the device that does not need the extra control signal to operate, including diodes, transformers, capacitors, inductors, and resistors. So passive component loss refers to energy loss occurring in the passive components of the circuit.

All these energy losses add up to reduce the overall efficiency of the LED driver. The efficiency of the drivers can be increased if the value of the components required in manufacturing is reduced to an extent without reducing its performance capabilities. Efficiency is one of the key factors in determining the LED driver to use in lighting as we move towards more energy-efficient lighting technologies.

$$LED\ Driver\ Efficiency = \frac{InputPower}{OutputPower} \times 100\% \tag{2.1}$$

The need for high-efficiency LED drivers is due for the following reasons:

- Energy and Cost Saving: High-efficiency LED drivers reduces operational cost. They require less input energy to provide the needed luminous output. Hence results in a low cost of power utility bills.
- Increased Product Lifespan: The higher the driver's efficiency, the lesser the heat it dissipates, and the longer the system's life.

2.2 Power Factor and Total Harmonic Distortion

Despite LED lighting's high luminous efficacy power quality of LED lighting has been a concern. Power Factor (PF) and Total Harmonic Distortion (THD) are key performance parameters that can limit the wide acceptance of LED lighting in the marketplace. Power quality for any AC lamp indicates how the lamp draws current when supplied with sinusoidal voltage from the AC mains, which in turn is non-linear for LEDs. As a consequence of this non-linear behaviour, existing LED lighting solutions to exhibit poor power quality scores in terms of both power factor ("PF") and total harmonic distortion ("THD").

$$Power\ Factor = \frac{TruePower}{ApparentPower} \tag{2.2}$$

Power factor is defined as the ratio of the real power absorbed by the load to the apparent power flowing in the circuit.The power factor formula can be expressed as:
True power is the actual power available to perform real work. Poor power factor means that power is being used inefficiently. LEDs running on a lower power factor draw more current than when it is running at a higher power factor. Hence, for the same wattage demand, the input power required by the LED with a higher pf will be less than that with the lower pf. And since output remains the same the efficiency will be higher in the case of high-power factor as input power required is less. LED lighting systems are driven by electronic LED drivers which have an inherently capacitive electrical characteristic. These drivers have an integrated active power factor corrector, resulting in a high-power factor > 0.95 at full load.

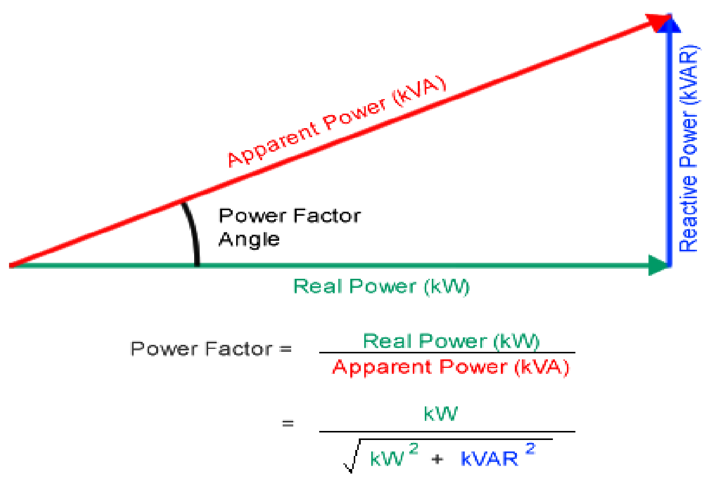


Fig 2.1: Power Triangle and Power Factor

THD is a numeric representation of distortion in the current waveform
relative to the sinusoidal voltage waveform on the AC mains. Distortion indicates how much harmonic current is flowing in the power lines. Harmonics are unwanted currents having frequency as multiples of the fundamental line frequency (e.g., 50 or 60 Hz). Harmonic currents can create additional voltage and power losses in the transmission lines, heat transformers, and capacitors, resonate with power factor correction capacitors, and/or overload neutral conductors. Uncontrolled harmonic currents in commercial facilities may lead to outages and even fires.

Total Harmonic Distortion is given by the equations (2.3):

$$Distortion\ Power\ Factor = \frac{1}{\sqrt{1+THD_i^2}} = \frac{I_{1,rms}}{I_{rms}} \tag{2.3}$$

where THD_i is the total harmonic distortion of the load current. I_{1rms} is the baseband component of the current, I_{rms} is the total current, and both are expressed by root mean square. The above definition assumes the voltage to be a sine wave without distortion. The total power factor can be acquired by multiplying the distortion power factor by the displacement power factor, which is also called the real power factor or power factor (2.4):

$$Power\ Factor = DPF \times \frac{I_{1,rms}}{I_{rms}} \tag{2.4}$$

It can be noticed that THD is inversely related to the power factor. So, an increase in power factor decreases the value of THD, thus reducing harmonics. As a result, the Power Quality is improved. This can be achieved by using a proper LED driver, that has power factor correction features to increase the power factor and mitigate the problem of developing harmonics.

2.3 Percent Flicker

The term percent flicker was given by Illuminating Engineering Society (IES). It is defined as the relative measure of the cyclic variation in the amplitude of light. The range has been given as 0-100%. The lower the percent flicker, the less significant the flicker.

Most commonly it is the result of the varying AC supplied to the light, which, after rectification (converting AC to DC), oscillates at twice the mains frequency (100 Hz or 120 Hz). Other potential causes include transformer incompatibility, dimmer compatibility, and the high-frequency ripple controls superimposed onto the main power signals of residences participating in load control programs.

The perceptibility of flicker can be subjective, especially at frequencies above 75 Hz. Even with flicker indexes up to 0.5, flicker was not immediately noticeable, however for those particularly sensitive to flicker, effects could potentially manifest in eyestrain and headaches if the light is used over prolonged periods. Individuals concerned about stroboscopic effects should use LED products with percent flickers of no more than 10% for 60 Hz line frequency, or 8% for 50 Hz AC mains.

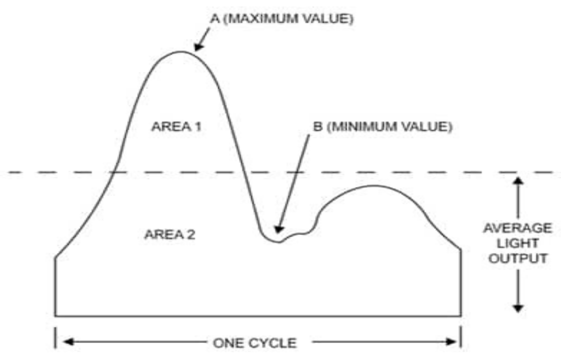


Fig 2.2: Schematic diagram of Percent Flicker

From the given diagram percent flicker can be calculated as:

$$Percent\ Flicker = 100 \times \frac{(A-B)}{(A+B)} \tag{2.5}$$

LED drivers with a constant current mode of operation can reduce percent flicker in LEDs. Input and output filtering in LED drivers reduce flicker further.So, choosing agood quality high-frequency switching LED driver that minimizes the AC component in the voltage and current ripples at the output which in turn will limit the modulation depth of the LEDs' flicker becomes important.

2.4 Constant Current Operation

LEDs are current-driven devices instead of voltage driven. The lumen output of the LED is proportional to the forward current passing through the LED. The higher the current is, the brighter the LED. However, a greater amount of heat is generated at the semiconductor junction region. This is because LEDs convert only around 50% of the energy into light and the remaining portion of the energy is released as heat. If the maximum allowable junction temperature is exceeded, high heat flux can lead to irreversible damage to the LED as well as reduce the optical power of the LED when the temperature is increased. So, limiting the current beyond a limit becomes mandatory.

An LED or an LED module that is connected to a constant voltage LED driver ultimately needs a current limiting device to regulate the current. This device can cause power loss and generate an additional thermal load. As a result, power efficiency is reduced and the LEDs becomes susceptible to high thermal stress, especially when current limiting is done using inefficient linear regulators or resistors. However, in a constant current LED driver no additional current limiting devices are required to limit the current to the LED below its maximum rated current. Constant current regulation in drivers ensures the LED module delivers consistent, non-fluctuating light output.

Thus, a good quality LED driver should be current controlled in nature. It increases the efficiency of the lamp, does not need the use of the current limiting device, and also gives an added dimming control capability to the user.

2.5 Protection Features

All LED drivers need various protections to prevent failures to protect the system where power suppliers are utilized. There are many types of protections related to voltage, thermal and current which improve the reliability and functionality of LED drivers.
A good LED driver must have the following protections:

1. Internal Over-temperature protection
2. External Over-temperature protection
3. Over current protection
4. Short circuit protection

5. Over-voltage protection
6. Input surge (Lightning) protection

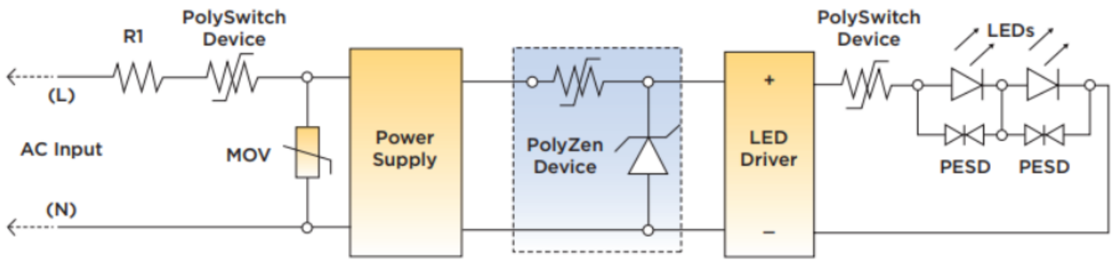


Fig 2.3: Protection scheme for LED Driver inputs and outputs.

2.6 Cost of the Driver

The major driver for LED Driver Market is the growing demand for LED in lighting applications such as retail outlets, and office complexes, and growing usage within the residential lighting application for households. The government is taking initiatives for radiant bulbs for power-efficient lighting and high-quality picture images, provided by the LED manufacturer. In addition to that, LED performance and robustness is driving the market growth of LED driver. For the large-scale adoption of LED drivers, the cost of drivers should be low. However, low cost may restrict the quality and functionality of the LED drivers. So, a balance should be struck between cost and quality. Depending on the use case of the LED bulbs a balance is to be achieved without compromising the basic requirements of the driver. A good LED driver thus should be economically viable for that particular use case.

2.7 Figure of Merits under consideration

In this paper, we will we analyzing a few of the parameters that have been discussed. The parameters that have been evaluated and compared to determine whether tapped inductor topology is a replacement for the Flyback topology are:

1. Efficiency
2. Power Factor
3. THD
4. Percent Flicker
5. Cost.

Other parameters are beyond the scope of this paper. MATLAB simulations have been conducted for both topologies to calculate and compare the values of the different figures of merits to provide a conclusive result.

Chapter Three

Design of LED Driver

It deals with the overall design of the LED drivers. It describes the specification of LED chips used. The configurations and linear model of the LED module have also been discussed. Calculations of both Flyback converter and Tapped Inductor topology parameters have been done in this chapter

3.1 Specification of LED Chip

LUMILEDS(LXML-PWC2) having the following specifications are considered in this study for designing a 60W LED module:

Table 3.1: LED Chip specifications (Acc. to Datasheet)

Rated Voltage	3V at 1000mA
Threshold Voltage	2.4V
Wattage	3W
Nominal CCT	5650K, Cool White
LED junction temperature	150° C
Luminous flux	320 lumens
Typical viewing angle	120 °

3.2 Design of LED Module

For the experiment, a 60W LED module has been considered. The LED module has been designed with 5 LED chips in series and such 4 such strings have been taken in parallel (i.e. Ns=5, Np=4), as shown in (3.1). The rated voltage of the module is 15V and the rated current is 4A.

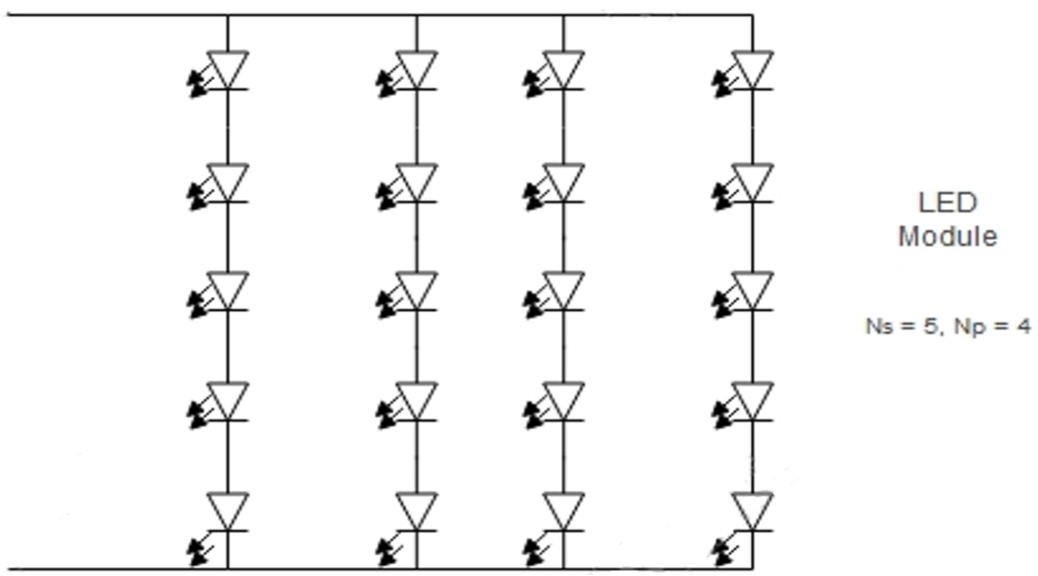


Fig 3.1: The 60W LED Module

The approximate linear model of LED has been considered to consist of a threshold voltage and dynamic resistance in series as shown in figure (3.2)

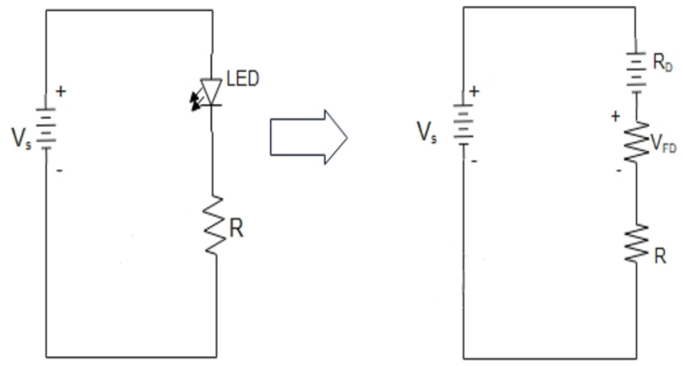


Fig 3.2: Linear Model of LED

The 60W LED load is tested with both the Flyback driver as well as with Tapped inductor driver under different operating conditions to determine values of various parameters.

3.3 Estimation of Flyback Driver Parameters

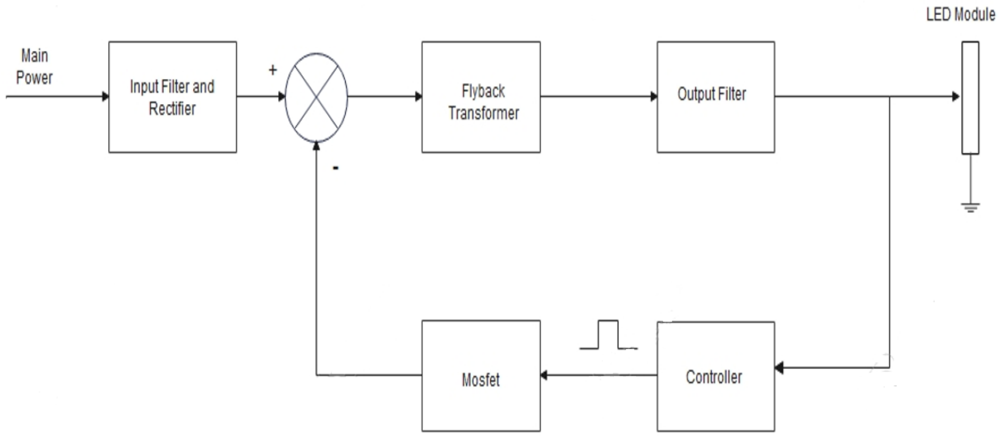


Fig 3.3: Block Diagram of Flyback Driver

3.3.1 Power circuit model:

It is responsible for providing power to the LED module. It consists of an EMI filter to decrease the harmonic content in the input current. The bridge rectifier converts AC to DC voltage. The design parameters of the flyback converter are the Switching frequency and duty cycle of the MOSFET switch.

The switching frequency has been taken as 50kHz and the maximum value of the converter duty cycle is 0.5. The value of mutual inductance (L_m) has been obtained from the equation (3.1)

$$L_m = 0.81 V_{in\_rms\_min}^2 * \frac{D_{\max}^2}{2P_{omax}f_s} \tag{3.1}$$

where

$V_{in\_rms\_min}$ is the minimum RMS value of the supply voltage.
f_s is the switching frequency.
P_{omax} is the maximum rated output power.
$D_{\max}$ is the maximum value of the converter duty cycle.

The output capacitance is given by the formula (3.2),

$$C_{out} = \frac{D_{\max} * I_o}{f_s * \Delta V_o} \tag{3.2}$$

where

$D_{\max}$ is the maximum value of the converter duty cycle.
f_s is the switching frequency.
I_o is the output current.
ΔV_o is the ripple voltage (taken as 1% of output voltage).

3.3.2 Control circuit model:

The LED driver model is current regulated. The control circuit regulates the output current of the LED driver according to the load requirement by generating pulses of the required width the output of the PID controller is compared with a sawtooth carrier signal of 50kHz to generate the required PWM gate width pulse. On receiving the pulse, the MOSFET becomes ON and as a result, the output voltage starts to build up to make the output current follow the reference signal. The current starts to flow once the output voltage of the driver is greater than 12V which is the threshold voltage of the 60W LED module.

The estimated values of Flyback driver parameters are:

Table 3.2: Design Parameters of the Flyback Driver

Supply voltage	230V,50Hz
EMI Filter	L_1= 1.2mH, C_1=0.1μF, R_1=0.001ohm
Switching frequency	50kHz
Maximum duty cycle	0.5
Mutual inductance (L_m)	0.9mH
Output Capacitance	330 μF
K_p, K_i	K_p=0, K_i=12

3.4 Estimation of Tapped Inductor Driver Parameters

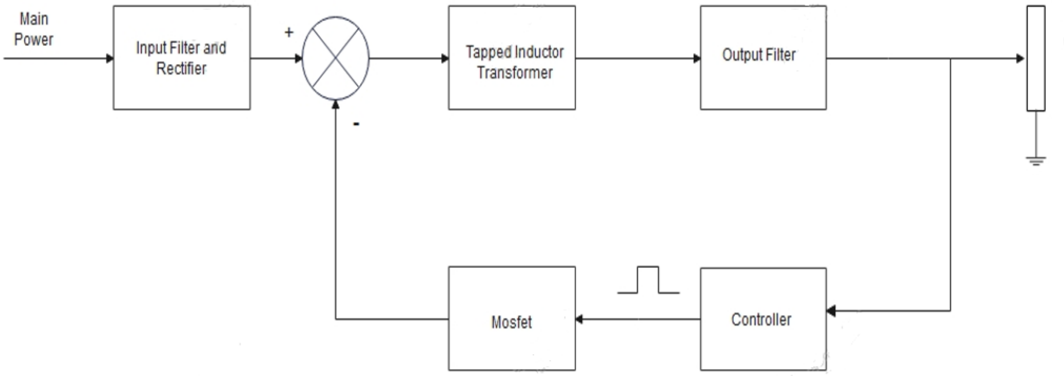


Fig 3.4: Block Diagram of Tapped inductor driver

3.4.1 Power circuit model:

The converter is a diode tapped buck-boost converter. It operates in CrCM mode and the diode tapped inductor behaves like an autotransformer. It consists of an EMI filter to decrease the harmonic content in the input current. The bridge rectifier converts AC to DC voltage. The design parameters of the flyback converter are the Switching frequency and duty cycle of the MOSFET switch.

The switching frequency has been taken as 50kHz. The efficiency of the converter is reduced in extreme cases of duty cycle so it is considered 0.4 for the study. The maximum voltage transfer ratio is calculated as (3.3):

$$M_1 = \frac{V_{dc}}{V_{in(max)}} = \frac{15}{230 * \sqrt{2}} = 0.046 \tag{3.3}$$

$$M_1 = \frac{-N_{DT} * d}{1-d} \tag{3.4}$$

where

d is the duty cycle

N_{DT} is a constant.

$$0.046 = \frac{-N_{DT} * 0.4}{1-0.4} \tag{3.5}$$

$$N_{DT} = 0.069$$

Again, the constant N_{DT} can be expressed as

$$N_{DT} = \frac{n_{11}}{n_{11}+n_{12}} \tag{3.6}$$

$$n_{11} + n_{12} = 400V(\text{say})$$

From equations (3.5) and (3.6),

$$n_{11} = 27.6 \approx 28$$

The output DC resistance for the diode tapped circuit is expressed as,

$$R_{dc} = \frac{V_{dc}^2}{P_{dc}} = \frac{15*15}{60} = 3.75ohm \tag{3.7}$$

For a switching frequency of 50 Hz and CrCM operation, the critical inductance for the converter is given by (3.8),

$$L_m = \frac{1}{N_{DT}} * \frac{R_{dc}(1-d)^2}{2f_s} \tag{3.8}$$

where

N_{DT} is a constant.
R_{dc} is the output DC resistance.
d is the duty cycle.
f_s is the switching frequency.

The output DC capacitor is calculated as(3.9)

$$C_o = \frac{V_{dc}d}{\Delta V_{dc} R_{dc} f_s} \tag{3.9}$$

where

V_{dc} is the output DC voltage.
d is the duty cycle.
ΔV_{dc} is the ripple voltage (taken as 1% of output voltage).
R_{dc} is the output DC resistance.
f_s is the switching frequency.

3.4.2 Control circuit model:

The LED driver model is current regulated and operates in CrCM mode. The control circuit regulates the output current of the LED driver according to the load requirement by generating pulses of the required width the output of the PID controller is compared with a sawtooth carrier signal of 50kHz to generate the required PWM gate width pulse. On receiving the pulse, the MOSFET becomes ON and as a result, the output voltage starts to build up to make the output current follow the reference signal. The current starts to flow once the output voltage of the driver is greater than 12V which is the threshold voltage of the 60W LED module.

The estimated values of Tapped inductor driver parameters are:

Table 3.3: Design Parameters of Tapped Inductor Driver

Supply voltage	230V,50Hz
EMI Filter	L_1= 1.2mH, C_1=0.1μF, R_1=0.001ohm
Switching frequency	50kHz
Duty cycle	0.4
Output DC resistance	3.75 ohm
Mutual inductance (L_m)	200 μH
Output Capacitance	230 μF
K_p, K_i	K_p=0, K_i=12

Chapter Four

Simulink Implementation and Evaluation of the drivers

This chapter deals with the Simulink Implementation and Evaluation of the driver topologies. Comparative analysis based on the various figure of merits has been performed to study the benefits and disadvantages of both the topologies.

4.1 Flyback Driver

The Flyback driver is simulated using MATLAB Simulink at different load conditions. The values of various parameters are evaluated at different load conditions.

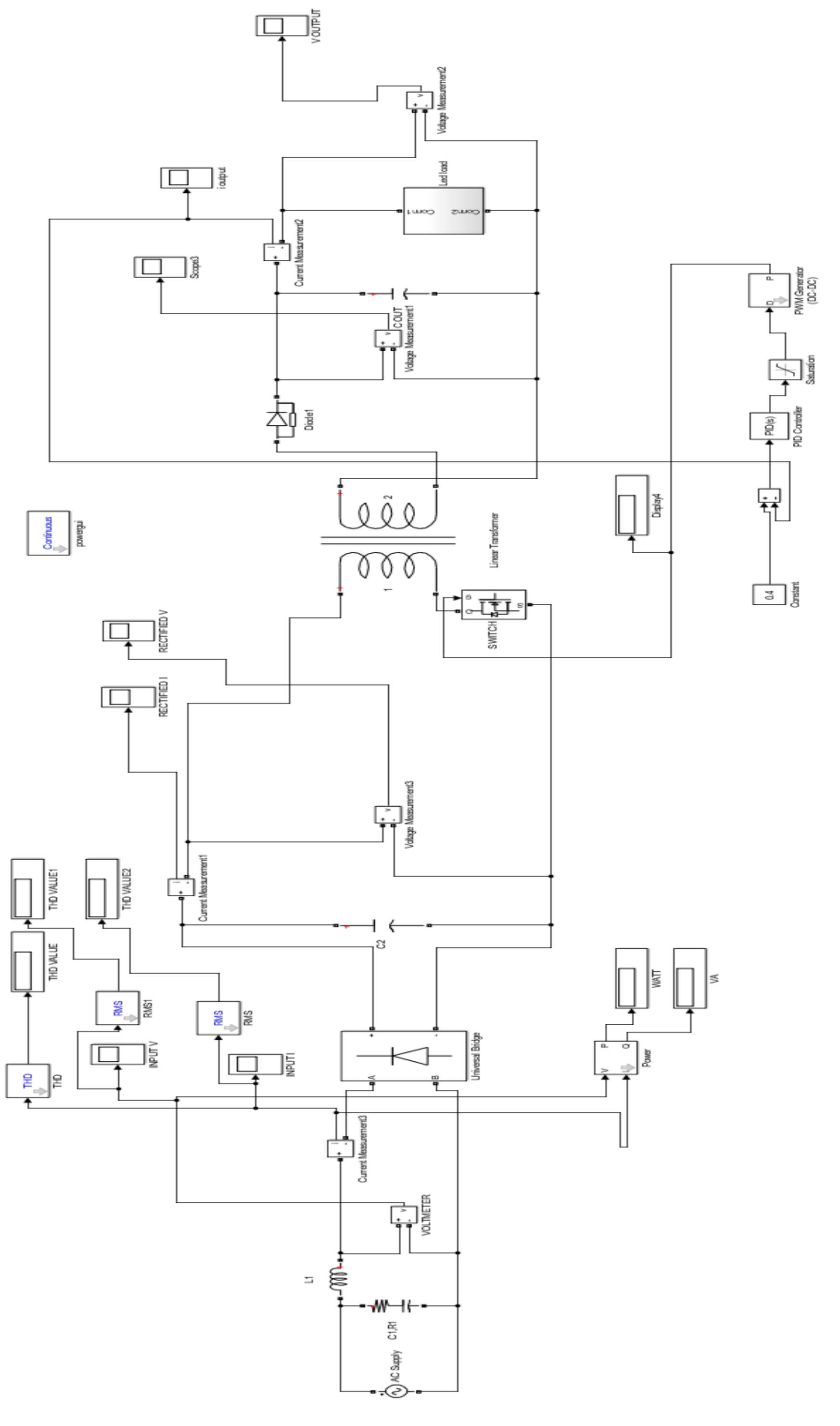


Fig 4.1: Simulated model of the Flyback LED driver

- **At Full load**: The input voltage is 230V and the input current is 0.3A. The reference current is set to 4A. The control circuit accordingly sends pulses to turn on the MOSFET. An output voltage of 15V and output current of 4A is seen across the load. The required wattage of 60W is achieved. The calculated values are as follows:

  Efficiency: 90%

  Power Factor: 0.97

  THD: 25%

  Percent Flicker: 3.82%

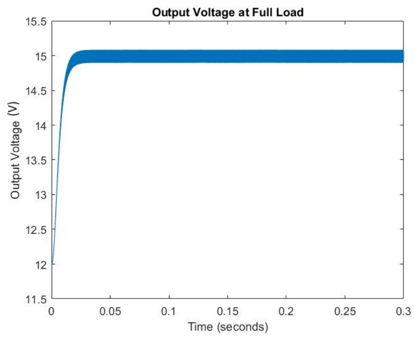


Fig 4.2: Output Voltage at full load

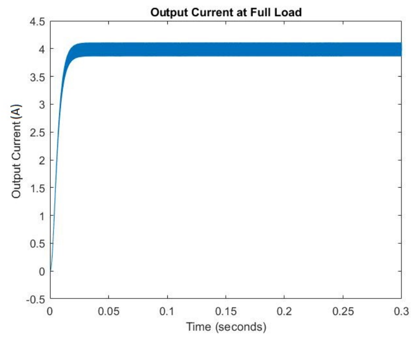


Fig 4.3: Output current at full load

- **At 75% of Full load**: The input voltage is 230V but the input current reduces to 0.22A. The reference current is set to 75% of full load current i.e. 3A. The output current follows the reference current and is 3A whereas the output voltage is 14.25V. The output power is 42.75W. The calculated values at this condition are:

  Efficiency: 89.2%

  Power Factor: 0.96

  THD: 29.2%

  Percent Flicker: 3.34%

  The efficiency has been reduced by 0.8% from the full load. The power factor has decreased from 0.97 to 0.96. THD has increased indicating a rise in harmonic content of the input current. Percent flicker has reduced.

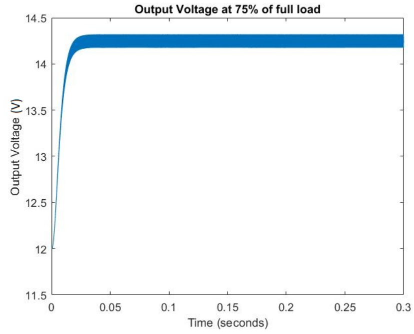


Fig 4.4: Output Voltage at 75% of full load

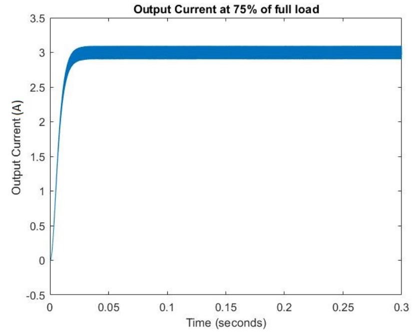


Fig 4.5: Output current at 75 % of full load

- **At 50% of Full load:** The input voltage is 230V but the input current reduces to 0.14A. The reference current is set to 50% of full load current i.e. 2A. The output current follows the reference current and is 2A whereas the output voltage is 13.5V. The output power is 27W. The calculated values at this condition are:

  Efficiency: 87.6%

  Power Factor: 0.96

  THD: 29.2%

  Percent Flicker: 3.4%

  The efficiency has been reduced by 2.4% from full load conditions. The power factor and THD remain unchanged from previous load conditions (75% of full load). Percent flicker has increased marginally to 3.4%.

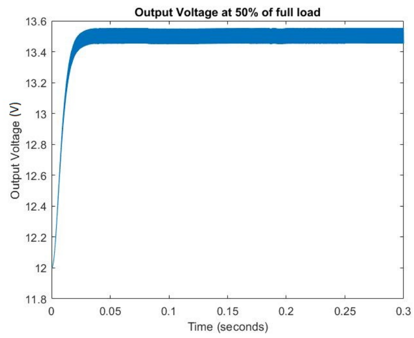


Fig 4.6: Output Voltage at 50% of full load

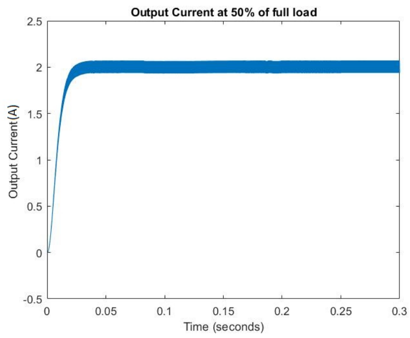


Fig 4.7: Output current at 50 % of full load

- **At 25% of Full load:** The input voltage is 230V but the input current reduces to 0.07A. The reference current is set to 25% of full load current i.e. 1A. The output current follows the reference current and is 1A whereas the output voltage is 12.75V. The output power is 12.75W. The calculated values at this condition are:

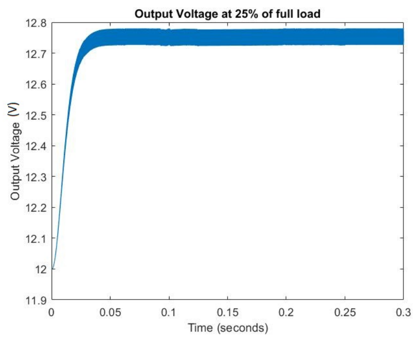
  Efficiency: 82.4%

  Power Factor: 0.96

  THD: 29.2%

  Percent Flicker: 3.86%

  The efficiency sharply drops to 82.4% at this load condition. The power factor and THD remain unchanged from previous load conditions (50% of full load). Percent flicker has increased to about 3.86%.



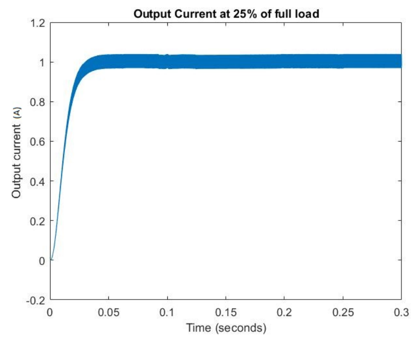


Fig 4.8: Output Voltage at 25% of full load

Fig 4.9: Output current at 25 % of full load

- **At 10% of Full load:** The input voltage is 230V but the input current reduces to 0.032A. The reference current is set to 10% of full load current i.e. 0.4A. The output current follows the reference current and is 0.4A whereas the output voltage is 12.3V. The output power is 4.92W. The calculated values at this condition are:

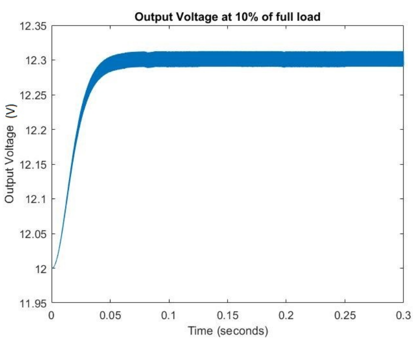
  Efficiency: 70.4%

  Power Factor: 0.95

  THD: 32.8%

  Percent Flicker: 3.87%

  The efficiency drops to a low of 70.4% at this load condition. The power factor has reduced to 0.95 and THD has increased to above 32% signifying a rise in harmonics. Percent flicker shows a negligible increase in its value at about 3.87%.



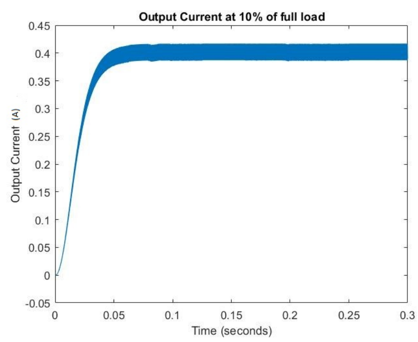


Fig 4.10: Output Voltage at 10% of full load

Fig 4.11: Output current at 10 % of full load

4.2 Tapped Inductor Driver

Tapped inductor driver is simulated using MATLAB Simulink at different load conditions for the same 60W LED load. The values of various parameters are evaluated at different load conditions.

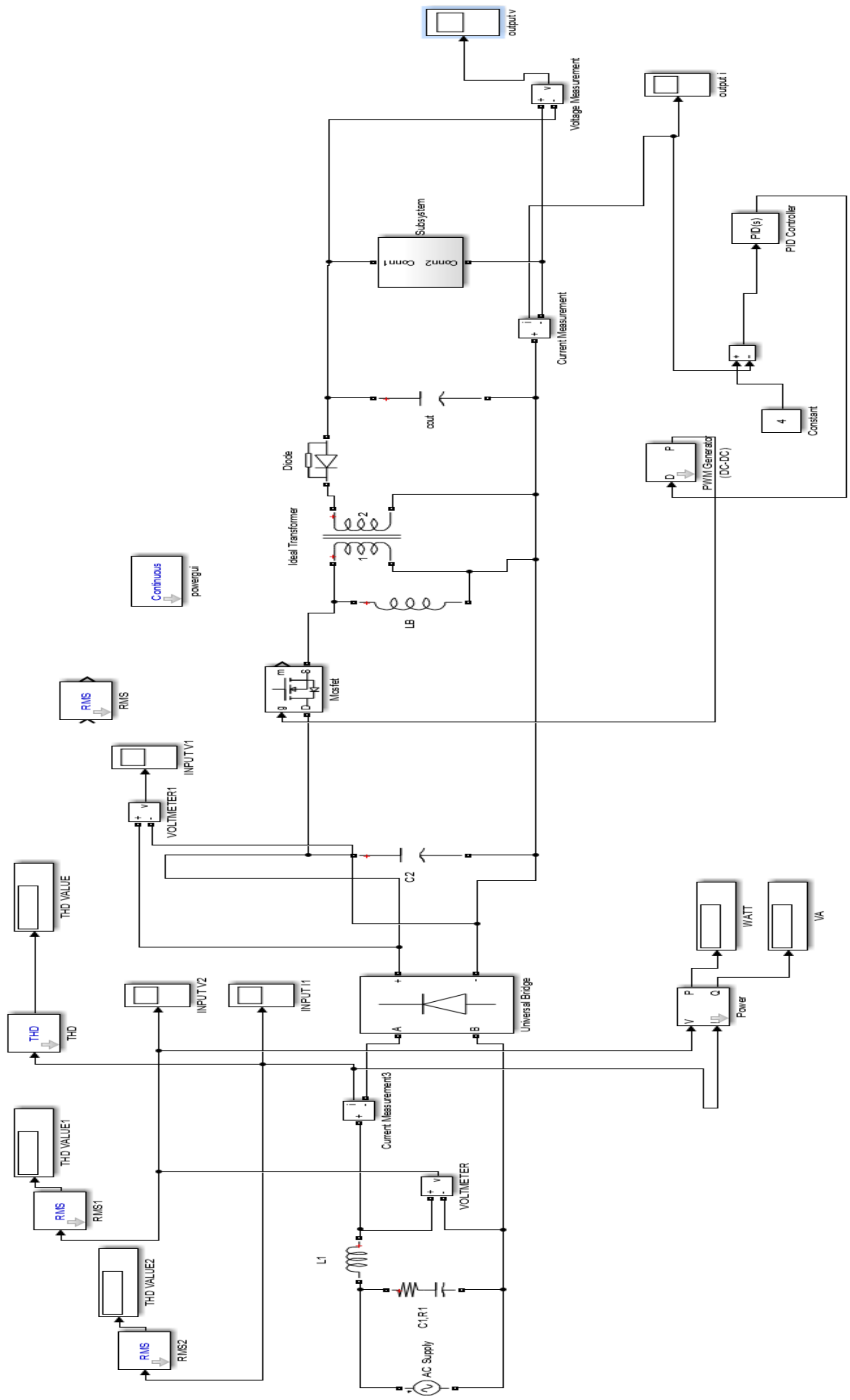


Fig 4.12: Simulated model of Tapped Inductor LED driver

- **At Full Load**: The input voltage and current for the full load condition are 230V and 0.277A. The reference current has been set to 4A. The output voltage and current are 15V and 4A respectively. Therefore, the output power is 60W. The calculated values are as follows:

  Efficiency: 95.7%

  Power factor: 0.984

  THD: 16.9%

  Percent flicker: 5%

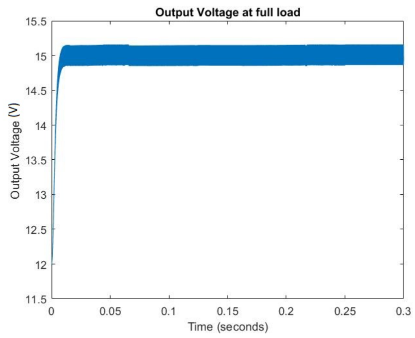


Fig 4.13: Output Voltage at full load

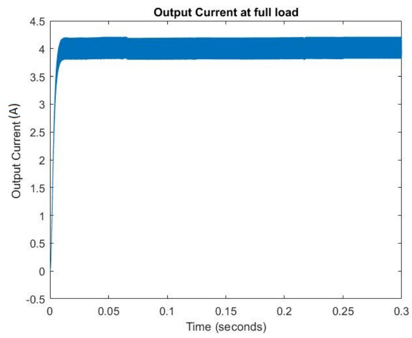


Fig 4.14: Output current at full load

- **At 75% of Full Load**: The input voltage is 230V and the input current is 0.199A. The reference current is set to 3A. The output current follows the reference current and gives an output power of 42.75W at an output voltage of 14.25V. The calculated values are as follows:

  Efficiency: 95.3%

  Power factor: 0.98

  THD: 20.3%

  Percent flicker: 5.14%

  The efficiency has been reduced by only 0.4% from the full load. The power factor has no noticeable change per se. THD has increased indicating a rise in harmonic content of the input current. Percent flicker has also increased marginally.

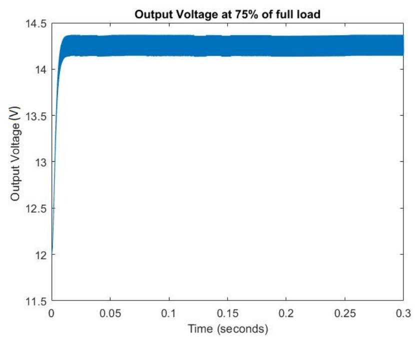


Fig 4.15: Output Voltage at 75% of full load

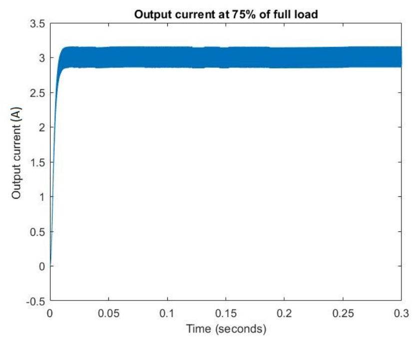


Fig 4.16: Output current at 75% of full load

- **At 50% of Full Load**: The input voltage is 230V but the input current reduces to 0.13A. The reference current is set to 50% of full load current i.e. 2A. The output current follows the reference current and is 2A whereas the output voltage is 13.5V. The output power is 27W. The calculated values at this condition are:

  Efficiency: 95%

  Power Factor: 0.97

  THD: 25%

  Percent Flicker: 5.4%

  The efficiency has been reduced by 0.7% from full load conditions. The power factor has reduced to 0.97 and THD gas increased to 25%. Percent flicker has increased marginally to 5.4%.

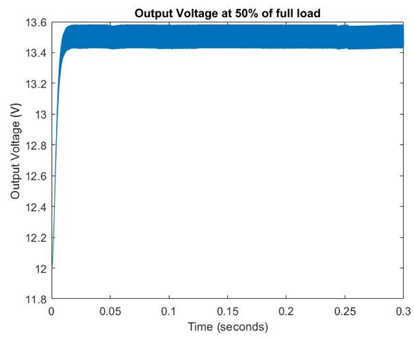


Fig 4.17: Output Voltage at 50% of full load

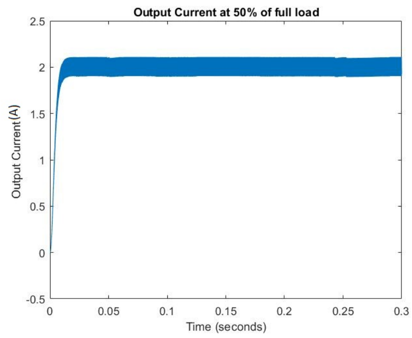


Fig 4.18: Output current at 50% of full load

- **At 25% of Full load:** The input voltage is 230V but the input current reduces to 0.062A. The reference current is set to 25% of full load current i.e. 1A. The output current follows the reference current and is 1A whereas the output voltage is 12.75V. The output power is 12.75W. The calculated values at this condition are:

  Efficiency: 92%

  Power Factor: 0.97

  THD: 25%

  Percent Flicker: 5.5%

  The efficiency sharply drops to 92% at this load condition. The power factor and THD remain unchanged from previous load conditions (50% of full load). Percent flicker has increased to about 5.5%.

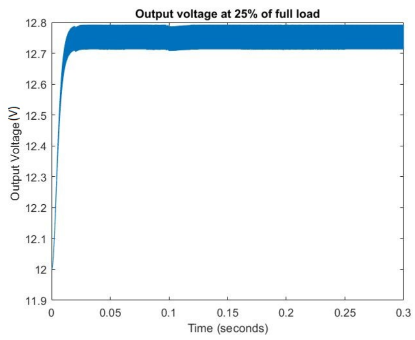


Fig 4.19: Output Voltage at 25% of full load

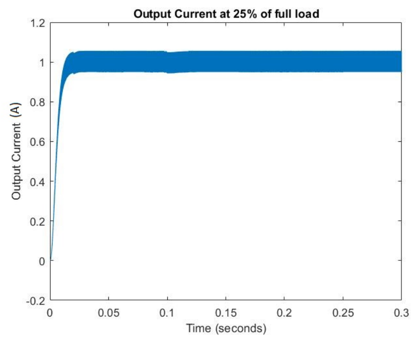


Fig 4.20: Output current at 25% of full load

- **At 10% of Full load:** The input voltage is 230V but the input current reduces to 0.025A. The reference current is set to 10% of full load current i.e. 0.4A. The output current follows the reference current and is 0.4A whereas the output voltage is 12.3V. The output power is 4.92W. The calculated values at this condition are:

  Efficiency: 87.5%

  Power Factor: 0.96

  THD: 29.2%

  Percent Flicker: 5.68%

  The efficiency drops to a low of 87.5% at this load condition. The power factor has reduced to 0.96 and THD has increased to above 29.2% signifying a rise in harmonics. Percent flicker shows a negligible increase in its value to about 5.68%.

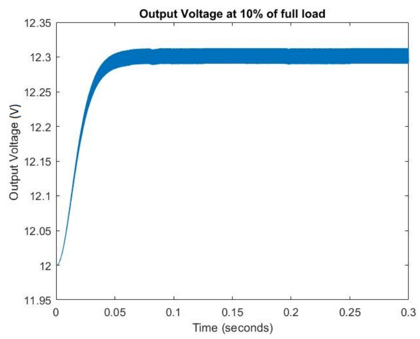


Fig 4.21: Output Voltage at 10% of full load

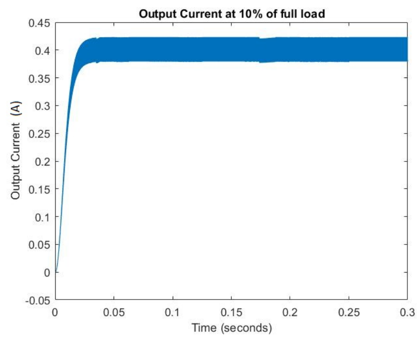


Fig 4.22: Output current at 10% of full load

4.3 Comparison of Figure of Merits

The two topologies have been simulated at the same load conditions. The two topologies have been compared on the following parameters:

4.3.1 Efficiency

Efficiency is one of the most important parameters for comparison. Since, the demand is rising for energy-efficient technology, to replace an existing one the replacement should perform better than the present technology it is trying to replace. The comparison of the two topologies shows that the Tapped Inductor driver outperforms the Flyback driver in terms of efficiency.

Table 4.1: Efficiency Comparison at Different Loads

	Efficiency (%)	
Load (%)	Flyback Driver	Tapped Inductor Driver
100	90	95.7
75	89.2	95.3
50	87.6	95
25	82.4	92
10	70.4	87.5

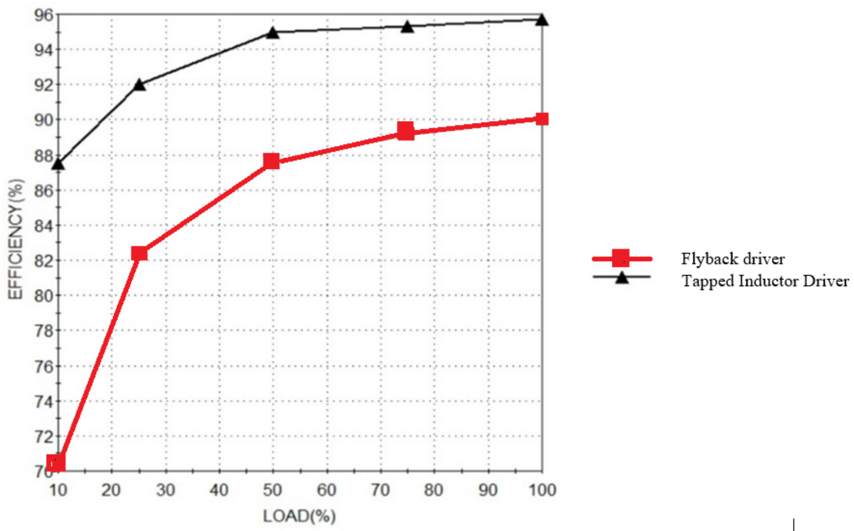


Fig 4.23: Comparison of Efficiency at Different Loads

In Table 4.1 , The efficiency of the Flyback driver ranges from a maximum value of 90% at full load to a minimum of 70.4% at 10% of full load conditions. However, the efficiency of Tapped

Inductor driver is far greater than the traditional driver. It reaches a maximum of 95% at full load and a minimum of 87.5% at 10% at full load. This is because of losses in the Flyback transformer due to leakage as well as more losses in passive components such as Inductor, and Capacitors which have greater value than the same components in the Tapped Inductor driver. All of these reduce the efficiency of the Flyback driver when compared to the Tapped Inductor Driver. In this parameter, the alternative driver performs better than the traditional driver.

4.3.2 Power Factor

The second parameter in consideration is the power factor. The higher the power factor, the higher will the useful output power produced from the same input power thus reducing the maximum demand of the supply.A low power factor means that the power delivery system has to be sized to deliver not just the required real power (kW), but also the unnecessary reactive power (kVARs). A poor power factor increases the current flowing in a conductor, and thus copper loss increases. A large voltage drop occurs in the alternator, electrical transformer, transmission, and distribution lines – which gives very poor voltage regulation. A higher power factor also reduces THD as it is inversely proportional to THD. Thus, a good power factor is quite crucial.

Table 4.2: Power Factor Comparison at Different Loads

	Power Factor	
Load (%)	Flyback Driver	Tapped Inductor Driver
100	0.97	0.984
75	0.96	0.98
50	0.96	0.97
25	0.96	0.97
10	0.95	0.96

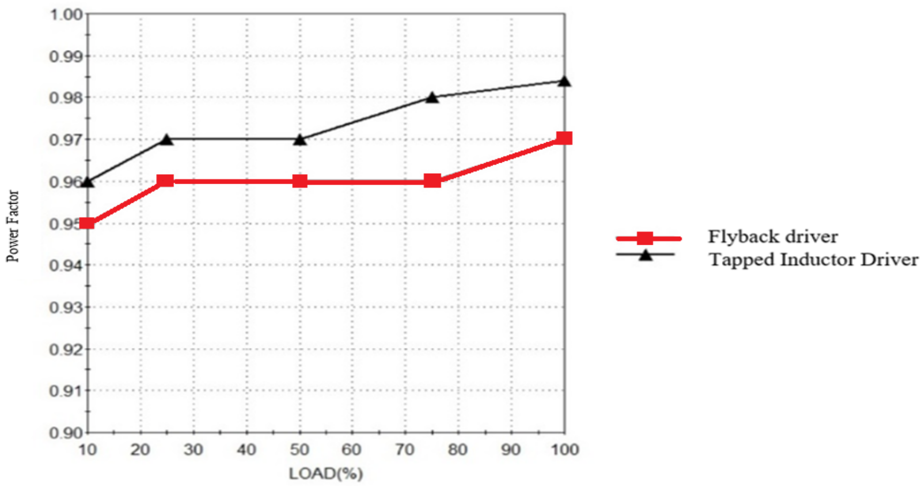


Fig 4.24: Comparison of Power Factor at Different Loads

In Table 4.2 ,on comparing the two topologies the Flyback driver has a maximum power factor of 0.97 at full load and a minimum power factor of 0.95 at 10% of full load. In the case of Tapped Inductor driver, the power factor is 0.984 for maximum load and 0.96 at 10% of full load. It also manages a pf of 0.97 even at 25% of full load which is the highest pf achieved by flyback driver full load only. So, in this parameter also alternative topology performs better than the traditional topology.

4.3.3 Total Harmonic Distortion

The third parameter is Total Harmonic distortion or THD. The harmonic distortion can negatively affect electrical equipment and lead to the degradation of individual components. Increased current leads to excessive heat and interference with over-the-wire communications. THD is inversely proportional to the power factor. The higher the power factor lower will be the THD. Hence, the circuits will have lower harmonic current and thus possess lower levels of nonlinearity.

Table 4.3: THD Comparison at Different Loads

	Total Harmonic Distortion (%)	
Load (%)	Flyback Driver	Tapped Inductor Driver
100	25	16.9
75	29.2	20.3
50	29.2	25
25	29.2	25
10	32.8	29.2

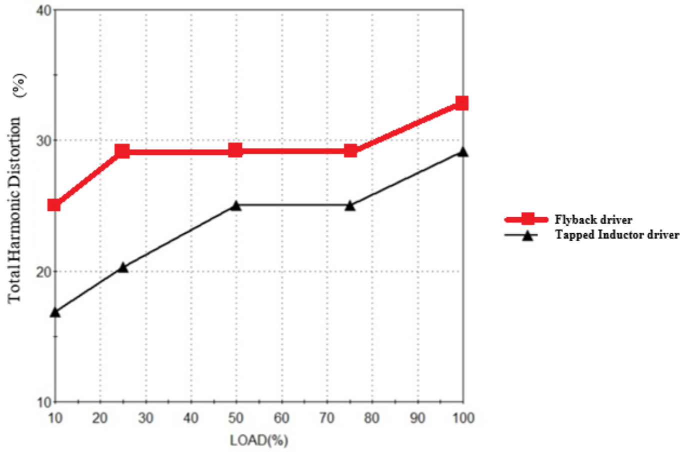


Fig 4.25: Comparison of THD at Different Loads

From Table 4.3 it can be seen that the THD is less for Tapped Inductor driver than the Flyback driver for the same load conditions. Thus, it has lower harmonic content and higher power quality. The THD ranges from 25-32.8% for traditional drivers and 16.9- 29.2% for alternative drivers.

4.3.4 Percent Flicker

The fourth parameter is percent flicker. Higher values of flicker can cause headaches, eye strain, and general eye discomfort. The lower the value, the better the lighting system.

Table 4.4: Percent Flicker Comparison at Different Loads

	Percent Flicker (%)	
Load (%)	Flyback Driver	Tapped Inductor Driver
100	3.82	5
75	3.34	5.14
50	3.4	5.4
25	3.86	5.5
10	3.87	5.68

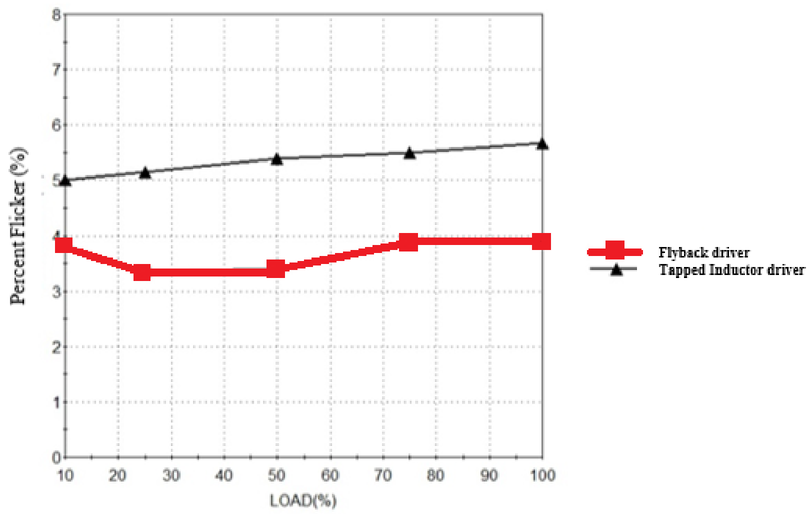


Fig 4.26: Comparison of Percent Flicker at Different Loads

The percent flicker is lower in the flyback driver when compared with Tapped Inductor Driver as seen in Table 4.4. In Flyback driver it is around 3 to 4% whereas in Tapped Inductor driver it is above 5%. In this parameter, both have a very low value of percent flicker and thus have little to no impact on humans. Here traditional driver outperforms the alternative driver.

4.4 Cost Analysis

The drivers are made up of components such as MOSFET, diode, inductors, capacitors, rectifiers, etc. All these components function together to produce the desired output. In both the topologies the fundamental components required are the same with 2 major distinctions:

1. The Flyback transformer in the Flyback driver is replaced by a Tapped Inductor transformer (which is an autotransformer) in Tapped Inductor Driver.
2. The values of components that are mutual inductance and output capacitance are reduced in Tapped Inductor driver.

As a result of the use of Tapped inductor transformer instead of a flyback transformer, the copper requirements are reduced to 1/k times that of an equivalent transformer circuit having the same turn ratio k. So, the cost of copper required reduces k times and hence manufacturing cost of the overall driver reduces.

Again, since the value of components required to manufacture is lower in the case of Tapped Inductor driver the cost of purchasing is also lower for the manufacturing company. They can thus provide the drivers to customers at a cheaper rate.

Table 4.5: Flyback Driver Component Costing

Component Name	Cost (in Rs) (acc. to mouser.in)
0.9mH Inductor	4.56
330μF Capacitor	16.86

Table 4.6: Tapped Inductor Driver component Costing

Component Name	Cost (in Rs) (acc. to mouser.in)
0.2mH Inductor	3.68
230μF Capacitor	7.13

The Tapped Inductor driver thus acts as a great cheaper alternative to the traditional Flyback driver. It not only costs less but is also a better driver in terms of efficiency, power factor, and THD. The manufacturers can manufacture this driver at low cost and make a profit whereas customers can buy them at lower prices. The customers will benefit from its energy efficiency and save money on electricity bills. This will facilitate the widespread adoption of LED lighting.

Chapter Five

Conclusion and Future Scope

This chapter deals with the conclusion based on the observations of the simulations. It also suggests the future scope of work on this thesis

The Tapped Inductor and Flyback topologies have been compared on various parameters to determine if the Tapped Inductor driver is a good alternative to the Flyback driver or not. The 95% efficiency of Tapped Inductor topology at full load outperforms the 90% efficiency of the Flyback topology. A similar trend is seen at different load conditions. Since tapped inductor LED driver has higher efficiency it reduces electricity demand, dramatic energy and maintenance savings, and a lower operating cost. The Power factor is also better for the Tapped Inductor driver at different load conditions which in turn reduces demand charges, increases load carrying capabilities in existing circuits, improved voltage, and lower system loss. The new topology attains a power factor of 0.984 whereas the flyback driver could only manage a maximum of 0.97 at full load. Since Power factor and THD are interlinked the THD results are also better for the new topology. The lower the THD values the better the power quality of the overall circuit. The THD values are lower for the Tapped Inductor (at 16.9% at full load) in comparison to the Flyback driver (at 25% at full load). The same trend is followed across the different load conditions. The Flyback driver performs better in the case of Percent Flicker. It has a lower Percent flicker than the Tapped Inductor driver. However, the Percent flickers are not high enough to cause much noticeable visual discomfort to the users. The proposed topology also provides more flexibility of operation as it can be operated in both buck and boost mode by varying the duty cycle. In doing cost analysis. It can be observed that the new topology also costs lower to manufacture than the traditional driver owing to lower values of parts and also savings in copper usage.
The only major drawback of the topology is that it does not provide isolation between the power circuit and control circuit which is preferred in these driver circuits to protect the individual circuit from the electrical shock that may damage the entire equipment.

The observations and comparisons of performance by the two driver topologies in the different figures of merits such as efficiency, power factor, total harmonic distribution, percent flicker, and cost help us conclude that the Tapped Inductor LED driver is a great low-cost alternative to the traditional Flyback LED driver.

Further studies can be done on this topology including physical implementation of the circuit to calculate real-world results. There is the scope of further reducing flicker by the use of voltage stabilization components. Comparison can be done with resonant LLC LED driver. Testing can be done with multicolored LEDs. Reliability Analysis can be performed on the Tapped Inductor Topology to have a better picture of its functional capabilities.

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