DESIGN OF LED DRIVER WITH POWER FACTOR CORRECTION FOR MULTI-COLOR LIGHTING SYSTEM

A Thesis

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Master of Science in Electrical and Electronic Engineering

by

Md. Azadur Rahman
Student No – 0417062243 P

Bangladesh University of Engineering and Technology (BUET)

Dhaka, Bangladesh

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Certification of Approval

The thesis title, "**Design of LED Driver with Power Factor Correction for Multi-Color Lighting System**", submitted by **Md. Azadur Rahman**, Student Number - **0417062243 P**, Session: April 2017, has been accepted as satisfactory in Partial Fulfillment of the Requirements for the degree of Master of Science in Electrical and Electronic Engineering on May 21, 2022.

Board of Examiners

Dr. Md. Ziaur Rahman Khan
Professor
Department of EEE,
Bangladesh University of Engineering and Technology,
Dhaka-1205.

Chairman (Supervisor)

Dr. Md. Kamrul Hasan
Professor and Head
Department of EEE,
Bangladesh University of Engineering and Technology,
Dhaka-1205.

Member (Ex-Officio)

Dr. A.B.M. Harun-ur-Rashid
Professor
Department of EEE,
Bangladesh University of Engineering and Technology,
Dhaka-1205.

Member

Dr. Md. Anwarul Abedin
Professor
Department of EEE,
Dhaka University of Engineering & Technology (DUET),
Gazipur, Bangladesh

Member (External)

DECLARATION

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Md. Azadur Rahman

DEDICATION

This thesis is dedicated to my beloved wife Sayeda Shafeli Parveen Shimi.

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Abstracts

This thesis presents a detailed design and control methodology of a single-stage multi-color or multi CCT fly-back LED driver with dimming option. Multi CCT LED lighting is required for various applications especially street lighting for different seasons or maintaining CCT in the class or office room lighting. However, in most of the reported multi CCT LED lighting applications, it was found that dual number drivers are used for controlling different CCT of LED lighting with limited variations of CCT of LED lighting. Unlike the existing multi CCT LED driver system, the proposed single driver will be used for producing multi CCT or multi-color LED lighting systems with dimming control. In the proposed driver, feedback circuit with power factor correction unit is incorporated to achieve desired power factor and reduction of total harmonic distortion of the input current. Furthermore, single-stage methodology is used in the circuit design where AC-DC rectification and DC-DC conversion take place in a single stage with the positive and negative cycle of input voltage thereby reducing power loss in the primary side of the driver. Flyback DC-DC converter is also used to achieve galvanic isolation between supply voltages and load. Hence, it ensures the safety of the circuit from the abnormal fluctuation of the input voltage. In the proposed driver, multi-string LED lights are connected in parallel. So maintaining current balancing in each string was challenging due to the different characteristics of LEDs. However, this challenge is addressed by controlling the LED string current by switching. In this work, a hybrid control scheme is developed which combines pulse width modulation (PWM) technique along with microcontroller control scheme in the LED strings to control the input and output current efficiently. Here red, yellow, and blue color LED lights have been mixed to produce the desired color. The look up table is used here to control the duty ratio of different color mixing. Applying the same methodology, warm white (3000K) and cool white (7000K) LED lights are also mixed to produce different CCTs of output lights. The timing sequence corresponding to color mixing ratios and CCTs is also explained. The dimming of the multicolor LED driver has been achieved by changing the current gain of the feedback circuit. Finally, the optimal parameters of the proposed circuit are determined for the best performances by analysing the key performance factors such as efficiency, power factor and THD. The resulting design gives better performance in terms of power factor (0.88), acceptable (40%) THD, and maximum efficiency which reaches up to 80%.

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating Current
AM	Amplitude Modulation
CCT	Correlated Color Temperature
CRI	Color Rendering Index
CCM	Continuous Conduction Mode
DCM	Discontinuous Conduction Mode
HPS	High Pressure Sodium
LED	Light Emitting Diode
PWM	Pulse Width Modulation
PFC	Power Factor Correction
SPD	Spectral Power Distribution
SIMO	Single Inductor Multiple Output
SMPS	Switch Mode Power Supply
SEPIC	Single Ended Primary Inductor Converter
THD	Total Harmonic Distortion

Chapter 1
Introduction

1.1 General discussion

Recently, solid state lighting such as light emitting diode (LED) has become more popular due to its added characteristics like efficiency, compactness, energy-saving and environmentally friendly operation [1]. LED light does not suffer from mechanical vibration, aging for switching, degradation of cathodes, or mercury loss, so the lifetime of LEDs is much longer than that of incandescent lamps and fluorescent lamps. When an LED is biased electrically in the forward direction of the p-n junction, it produces an incoherent narrow-spectrum of light. This effect is a form of electroluminescence. However, the color of the emitted light depends on the composition and condition of the semiconducting material used, and can be infrared, visible, or ultraviolet light [2]. The power consumption of LEDs is about one tenth of that of incandescent lamps and half of that of fluorescent lamps [3]. Conventionally, an LED is a solid-state device that runs on direct current (DC). For this reason, alternating current (AC) is required to convert into DC in a standard LED driver. Besides, to ensure secure power supplies for LED lighting devices, it is better to isolate the source and the load so that in the event of a high surge current, it does not destroy LEDs. In addition, while designing LED drivers for AC system, total harmonic distortion (THD) and input power factor (pf) are important parameters to be considered in order to achieve maximum efficiency as well as reduce deterioration in the main supply line. In many cases, white LEDs are taken into account as the alternative to High Pressure Sodium (HPS) lights for street lighting due to their expanded luminous capacity, constancy, and required color rendering qualities. LEDs have two other major advantages. The first is that the shape of their light spot can be easily controlled for various purposes; the second is that their spectral power distribution (SPD) can be customized using different kinds of LED chips or different amounts of phosphor coating. Thus, the correlated color temperature (CCT) and illumination performance of an LED light source can be easily customized as well [4]. In another study [5] it was found that 81.08% of students adjust light levels in the classroom to impact mood, attention, and engagement regarding specific activities and times of day. People feel comfortable driving on the road and walking along the pedestrian path when street lights have a low CCT value (less than 4000K). However, low CCT lowers the color rendering index (CRI) and luminous efficacy of a light source, so a reasonable CCT should be selected for pedestrian lighting. At the same time, while choosing CCT for street lighting, fog penetration ability should be considered as an important factor [4]. Recent studies have also shown that the right light (provided by multi-color LED lighting) assist in changing the human state of mind, either by enhancing readiness during work or by supporting appropriate rest through the creation of proper hormones (melatonin) [6]. Dynamic spectral and intensity control of lighting also helps in the reduction of circadian rhythm disruption [7]. The spectral tunable property of multi-color lighting systems provide an optimum light technique at every stage of the crop's growth and increases their productivity in horticulture [8]. To meet all these requirements, the design of a multicolor or multi-CCT LED driver is needed so that with the single LED driver, multiple CCT or multicolor lighting can be achieved. Besides, the brightness of LED lighting can be controlled with the same driver, keeping CCT constant.

1.2 Background and present status of the problem

Multi-color LED lamps have the possibility of providing quality lighting with high CRIs. Color tunable light sources may be used for mood lighting, which affects the emotional feeling of humans [5]. Also, in a recent study, CCT tunable LED light sources have been used in street lighting to get better visual performance [4]. The demand for independent CCT and illumination controller light sources for various applications is rapidly increasing. A switched mode power supply (SMPS) LED driver for lighting applications is proposed in [9]. A current balancing modular driver for a multichannel LED is proposed [10]. This capacitor-based passive current balancing system has inferior reliability due to numerous capacitors and diodes. A single-stage multiple outputs LED driver with PFC was demonstrated in [11]. However, this driver is designed for single CCT LED lights. In a recent work, a monolithically integrated Single Inductor Multiple Output (SIMO) RGBW LED driver is presented for drone applications [12]. This circuit is applicable for battery operated LEDs not designed for AC application. The control algorithm for CCT and Illuminance control of an LED lamp is proposed in [13] where Grassmann's law of color mixing and McCamy's formula of CCT have been used. Power factor correction (PFC) was not considered here. A low cost solution of LED driving, designed for tunable white lighting systems, were presented where two LED drivers are used one for controlling warm LED string and another for cool LED string [6]. Nonlinear approaches to controlling the luminous intensity and CCT of LED lamps are presented in [7][14]. However, these works mainly focused on the color mixing methodology, not on the driver design. PFC and harmonics improvement are not also considered. A single-stage LED driver for monocolor with PFC was designed in [8]. This work proposed a non-isolated driver which has problem of safety. So, an efficient multi-color isolated LED driver with a PFC unit is yet to be investigated.

1.3 Basic principle and characteristics of LED

LEDs are constructed from semiconductor materials doped with impurities to form p-n junction. When a potential difference is applied across the p-n junction, the electrons from the n-side are able to acquire sufficient energy to be excited into the conduction band and subsequently inject into the p-side. In Fig 1.1 shows the energy band diagram of a LED p-n junction. When electrons combine with holes on the p-side, electrons will relax back into the valence band and energy will be released in the form of photons. The wavelength of the produced light relies on the size of the band gap. In other words, the color of an LED can be customized by proper selection of semiconductor materials.

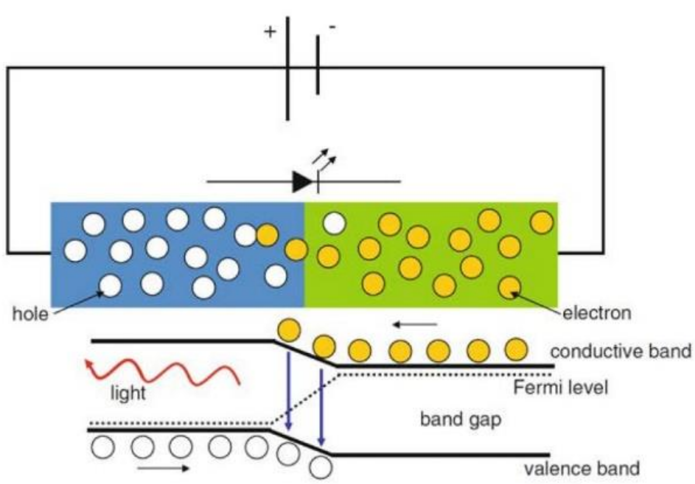


Fig1.1: Energy band diagram of a typical LED. [15]

Light output of LEDs is proportional to the amount of injected current while the current-voltage relationship of LEDs is characterized by an exponential function, which is given by (1.1) in terms of the forward voltage and junction temperature of LEDs. From Fig 1.2 it can be seen that the forward voltage of LEDs is nearly constant even if the current is drastically changed. Therefore, LEDs are often treated as a type of constant-voltage device which should be driven by controllable current source.

$$I_{LED}=I_S(e^{qV_{LED}/kT}-1) \qquad 1.1$$

Where, I_s is the saturation current, q is the electron charge, k is the Boltzmann's constant, and T is the absolute temperature of LED in kelvin.

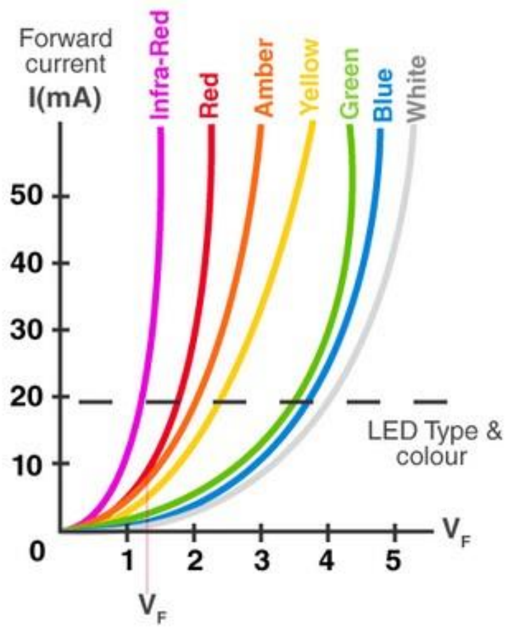


Fig1.2: V-I characteristic of LED.

1.4 LED driver basics

LED driver changes the power supply to a specific voltage and current to drive the LED voltage converter. In general, the input of the LED driver includes the high voltage AC, the low voltage DC, the high voltage DC, the low voltage and high frequency AC (such as the output of the electronic transformer). Characteristics of ideal LED driver should have high reliability, high efficiency, high power factors and surge protection for high current. The core components of LED driver includes switch controller, inductor, switch component (MOSFET), feedback circuit, input filter, output filter and so on [3]. LED driver circuit can be constructed by the DC-DC buck, boost, buck-boost, cuk and fly-back converter. Basically, two types of LED drivers exist i.e. constant current and constant voltage LED driver. The output current of the constant current driver circuit is constant, but the output DC voltage varies in a certain range with the different size of the load. Smaller the load resistance lower is the output voltage, the greater the load resistance the higher is the output voltage. For constant current LED driver, attention should be paid to the maximum withstand current and voltage used, which restricts the number of LEDs used. In case of dimming of constant current driver additional complex circuitry like constant current reduction is required to control the current [16]. Whereas for constant voltage LED driver the output voltage is fixed, while the output current changes with the increase or decrease of load. The brightness will be affected by the voltage changes that are rectified in constant voltage driver.

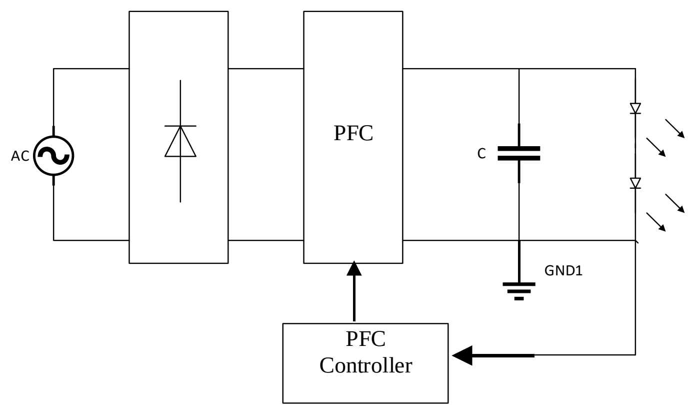


Fig 1.3: Schematic diagram of basic LED Driver. [15]

1.5 Multicolor LED lighting system

The wavelength or color temperature of an LED light depends on the band gap energy of the materials of p-n junction. Different color of LED lights are made of numerous types of semiconductor materials. For example, aluminium gallium arsenide (AlGaAs) produce red and infrared light, aluminium gallium phosphide (AlGaP) produces green and aluminium gallium indium phosphide (AlGaInP) produces high brightness orange-red, orange, yellow and green light, etc [2]. Mono-color LED light is produced by a single type of LED p-n junction material. However, conventionally there are two methods followed for producing high-intensity white light. Firstly, white light or different colors are produced by blending colors: red, green, yellow, and blue which are called dynamic multi-colored white LEDs. In principle, this type of white or different color LED light has higher quantum efficiency, however, it needs a complicated circuit design for LED driver. The second method white light is produced by phosphor coating of a mono-color LED light mostly phosphor coating is given on the blue LED. Construction of this type of white LED light is easier than multi-colored LEDs however quantum efficiency is comparatively less and is having other phosphor-related degradation issues.

1.6 Major challenges in designing multi-string LED driver

Due to production of multicolor LED lighting and insufficient luminance emitted from a single LED module, a large number of LEDs are required to be connected in series, parallel, or series-parallel. Multiple light sources are required to satisfy the high light intensity requirement for large-area and high-power lighting applications such as street light, traffic signaling, and general lighting. Although a series connection of LEDs offers a simple solution but it requires a high turn-on voltage which poses safety concern to a LED driver. Also, it could result in higher failure probability of the bulky LED string. Therefore, driving multiple LED strings collectively with a common bus voltage is a more viable solution in practice. However, their V-I characteristics can differ from one another due to the manufacturing spread and negative temperature coefficient of LEDs [15]. In conjunction with the non-linear V-I characteristics of LEDs, equal current sharing among multiple LED strings is difficult to be assured even if they are attached to a common bus voltage, which can lead to non-uniform light output or even rapid deterioration of LEDs. Fig 1.4 illustrates the current imbalance situation resulting from different V-I characteristics of LEDs for which the current deviation with different types of LEDs. As a result, current balancing is another important design objective of LED drivers for equalizing the currents among multiple paralleled LED strings.

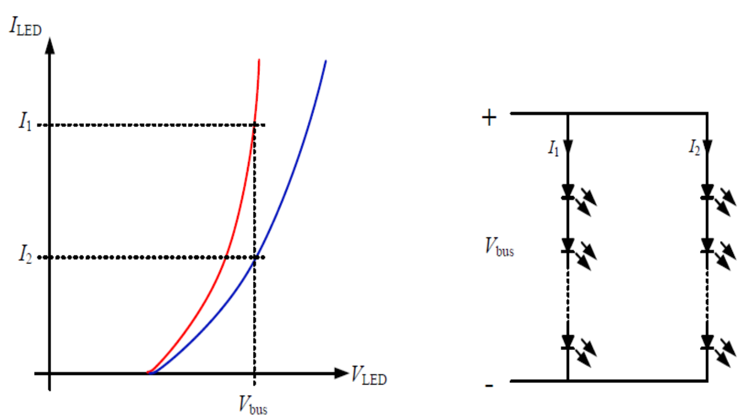


Fig 1.4: Current imbalance of LED strings under different V-I characteristics. [15]

Existing current balancing mechanisms can be classified as passive or active approach. In case of passive approach, capacitors, inductors or combination of both can be used for controlling the current. A bidirectional current path must be made available in this approach to enable the AC current flow which is usually accomplished by connecting a bridge rectifier before an LED string [15]. In this type of approach the current accuracy is heavily dependent on the tolerance of component values or the capacitive/inductive reactance. On the other hand, the active approach uses multiple linear or switch-mode DC-DC current regulators to drive each LED string independently such that accurate current balancing can be achieved by individual current regulation. Although current balancing or independent control can be easily achieved by the linear-mode current regulators, the control complexity increases with the number of LED strings. Similarly, as LED strings are driven by their dedicated switched-mode current regulators, current balancing or individual dimming can be simply accomplished by either applying identical or corresponding voltage or current references to the regulation loops. In general, all dimming methods i.e. amplitude modulation (AM) or pulse-width-modulation (PWM) can be implemented readily without major hardware modifications. However, the control complexity and the number of components increase rapidly with the number of LED strings.

1.7 Objectives and scope of this thesis work

The objectives of this work are:

- To design a single-phase multi-output AC-DC fly back rectifier topology to feed a single-phase multi-color LED driver.
- To develop timing sequence for enabling the color mixing or variable CCT operation of the proposed driver.
- To incorporate output voltage control in the proposed LED driver for tunable dimming lighting level.
- To develop and simulate the appropriate control strategy with a simple switching technique for input power factor improvement and input current harmonic reduction of the proposed rectifier.

***Possible outcome of the research*:**

- Successful design of such system will result in a high power factor AC LED light with tunable color and illumination level.

1.8 Organization of the thesis

A new topology of a power factor corrected integrated single stage multicolor LED driver is proposed and developed in this thesis. The operation and performance of the circuit is illustrated by simulation. **Chapter-1** is the introductory chapter with brief discussion about background of thesis. This chapter's summary gives the motivation, aim and objective of the thesis. **Chapter-2** describes different types of DC-DC converter in particular fly-back topology is discussed in detail. In this chapter different types of control strategy, multistring LED lighting system, color mixing, CCT and dimming control policy are also discussed. In **Chapter-3**, a new topology of single stage constant voltage fly-back LED driver along with PFC feedback circuit has been proposed. Basic working principle of the proposed LED driver is described. Performances of the proposed LED driver in terms of power factor, THD and efficiency have been analyzed through simulation and best set of parameters are selected for the proposed single stage LED driver. **Chapter-4** based on the proposed fly-back LED driver model, multicolor fly back LED driver with control scheme is proposed. Moreover color mixing, CCT control and dimming of LED lighting methodologies are proposed. Simulation results for each model is analyzed and discussed with timing sequence diagram in this chapter. **Chapter-5** concludes the thesis with conclusion and suggestion on future works followed by references.

Chapter 2
Background Study

LED drivers are operated at low DC voltage, however, the supply voltage in our country is AC with high voltage which needs to be rectified as well as regulated to lower DC voltage to fulfill the requirement of LEDs. Thereby, DC-DC voltage regulation, as well as control mechanism, are mandatory for LED drivers. In this chapter, different types of DC-DC converters with control methods, different types of existing driver topologies, color mixing, and dimming control policies have been discussed subsequently.

2.1 DC-DC converter

A DC power supply is utilized in a large portion of the electronic appliances where a steady voltage or consistent current is needed. DC converters are employed for the DC conversion. A DC to DC converter bridges the voltage from a DC source and the voltage of supply gets converted into another DC voltage level. The primary function of DC to DC converter is to match the secondary load to the primary power supply, to provide safe operation of the circuits and to provide protection against the faults. Generally, DC to DC converters in electronic circuits uses switching technology. Switched mode DC-DC converter changes over the DC voltage level by depositing the input energy momentarily and then discharges that energy at different voltage output. The deposition process is carried out either in magnetic field components like an inductor, transformers or electric field components like capacitors. Switching conversion is more efficient than linear voltage regulation, which dissipates undesirable power as heat. Most DC-DC converters are intended to move uni-directionally from input to output. But the switching regulator topologies can be intended to move bi-directionally by replacing all diodes with separately controlled active rectification. By altering the duty cycle of the charging voltage the amount of power transferred to a load can be controlled. This could also be termed as SMPS.

2.2 Non isolated DC-DC converter

Non-isolated converters are used when small voltage change is required. Both the input and output terminals are connected in a common ground of this circuit. However, the disadvantages of this type of converters are that it cannot give protection from high electrical voltages and have more noise. The following are the different types of non-isolated DC-DC converters.

2.2.1 Step-down (Buck) converter

It is a kind of step down DC-DC converter used for converting power from higher level to lower level according to the specific requirements. The polarities are similar to the input. The Fig 2.1(a) shows the fundamental diagram of a buck converter. Buck converter declines the voltage by elevating the current not dissipating power as heat. Output voltage will heavily rely on the duty ratio (D) of the switching cycle. $V_{OUT}=V_{IN}*D=V_{IN}*t_{ON}/T$ where t_{ON} is the on time and T is the period of cycle. The primary advantage of this type of converter is its simplicity, low cost and losses. Higher efficiencies greater than 97% can be obtained easily. The requirement of PWM regulator feedback circuit is a minimum output ripple to regulate properly, as the regulation is typically cycle- by-cycle which is basically a drawback in this case [17].

2.2.2 Step up (Boost) converter

A step-up circuit is used to develop a higher voltage than the input voltage. It is called as a boost. The polarities are same as in the input. A simplified circuit diagram is shown in Fig 2.1 (b). It is a class of SMPS which consist of two semiconductor switches. Filters are also connected to the output of the converters in order to reduce the ripple content in the output side of the converter. Disadvantages of this type of converter are its pulsed input current which can cause EMI and voltage drop issues in the input leads. The output cannot be switched off without adding a second switch in series with the input as disabling the PWM controller alone does not disconnect the load from the input and destructive currents might flow that will quickly destroy both the converter and the load.

2.2.3 Buck-boost converter

In buck-boost converter, the output voltage can be varied from the input voltage in order to boost or buck the voltage. It is like a fly back converter, but instead of using a transformer it only has an inductor. The common usage of this converter is to reverse the polarity. The simplified diagram in Fig. 2.1 (c) shows the basic circuit diagram. This topology is suitable for generating negative voltages only. The advantage of a buck-boost converter is that the input voltage can be higher or lower than the regulated output voltage. Buck-boosts are additionally exceptionally valuable for settling photovoltaic cell outputs. As the voltage-current relationship changes, a buck-boost can be applied for maximum power point tracking (MPPT) so that the input/output voltage ratio can be continuously adjusted. Due to limited number of components, the cost and complexity of the converter are minimized. Disadvantages of this converter are the inverted output voltage and floating active MOSFET switch. In order to turn on the switch special circuitry which is known high side driver is required. For these reasons this topology of converter is seldom used in the practical application.

2.2.4 Ćuk converter

The ćuk converter converts an input voltage into a regulated, inverted output voltage higher or lower than the input voltage depending on the duty cycle. The simplified diagram in Fig. 2.1 (d) shows the basic circuit diagram. It is essentially a boost converter capacitive coupled to an inverted buck converter. The biggest disadvantage of the ćuk converter is the heavy dependence on capacitor. All of the current flowing from input to output must go through this capacitor which must be non-polarized as the voltage across it reverses with each half cycle. The high ripple current generates internal heating which limits the operating temperature. In practice, bulky and expensive polypropylene capacitors must be used in this type of converter. Furthermore, the PWM control loop must be very carefully designed for stable operation. With four reactive components (two inductors and two capacitors), great care must be taken not to create unwanted resonances in the control circuit.

2.2.5 SEPIC converter

One of the disadvantages of buck/boost converters is the inverted output voltage. This problem can be eliminated by a two stage design called the Single Ended Primary Inductor Converter (SEPIC). Essentially the design is similar to a ćuk converter except in a SEPIC topology, the inductor and diode are swapped around. The primary drawbacks are that the SEPIC converter has a pulsed output current waveform similar to a conventional single stage buck/boost converter.

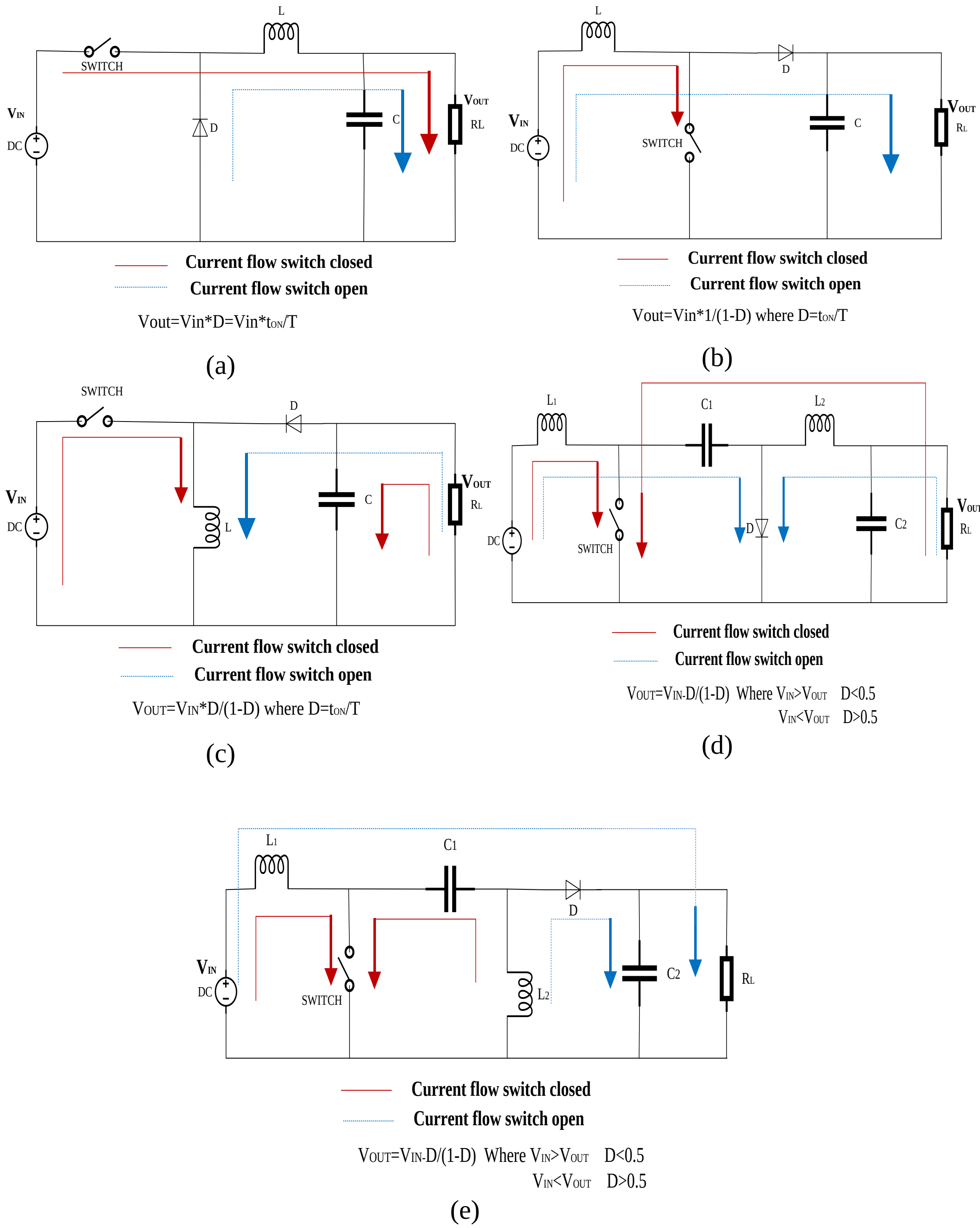


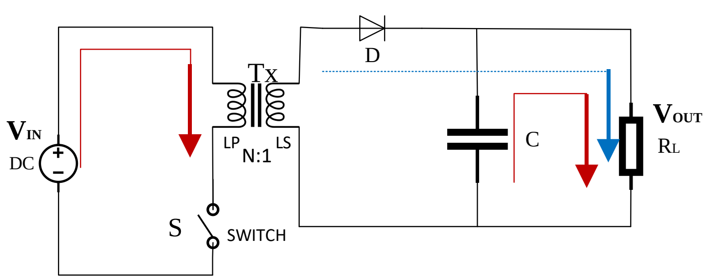
Fig. 2.1: Different types of non-isolated Converters (a) Buck converter (b) Boost Converter (c) Buck-Boost Converter (d) Ćuk Converter and (e) SEPIC Converter. [17]

2.3 Isolated DC-DC Converters

In these types of converters isolation between input and output terminals of the converters persists and transformer is used to transfer of energy from input to the output. They have high isolation voltage properties. It can block the noise and interference thus permits to generate a cleaner DC source. The disadvantage of using a transformer is that the energy transfer from primary winding to secondary winding involves additional losses. They are categorized into two types.

2.3.1 Fly-back DC to DC converter

The working principle of this converter works is as same as the buck-boost converter of the non-isolating category. The difference is it uses a transformer to store energy instead of an inductor. The fly-back converter converts an input voltage into a regulated output voltage by storing energy in the transformer core during the ON time and transferring it to the secondary during the OFF time. In this converter the primary and secondary windings of the fly-back transformer does not carry current simultaneously and in this sense fly-back transformer works differently from a normal transformer. As the primary and secondary windings of the fly-back transformer do not operate simultaneously they are more like two magnetically coupled inductors and it may be more appropriate to call the fly-back transformer as inductor-transformer. Fig. 2.2 shows the simplified block diagram of fly back converter.



Current flow switch closed

Current flow switch open

$V_{OUT}=V_{IN}*1/N*D/(1-D)$ $V_{IN}>V_{OUT}$ and $V_{IN}<V_{OUT}$

Fig.2.2: Fly-back Converter.

When switch S is closed, a current I_S flows through the primary winding of the transformer T with an inductance of L_P with a rise rate of V_{IN}/L_P. During this time, energy is stored in the primary winding and no current flows through the secondary winding L_S to the load. This phase is called energy storing phase of fly back converter. The load current is provided at this time by the capacitor C. When switch opens, the collapsing magnetic field in the transformer causes the voltages at the primary and secondary windings to change their polarity. The energy stored in the primary winding is now transferred to the secondary winding and this phase is said to be fly back stage. The secondary voltage rises sharply and a pulse of current flows into the load and C, decreasing at the rate V_{OUT}/L_S. Fly back AC-DC rectifier normally consists of diode bridge rectifier and fly back DC-DC converter which is usually used for step-up or step-down purposes. Input to the circuit may be unregulated DC voltage derived from the utility AC supply after rectification and some filtering. The ripple in DC voltage waveform is generally of low frequency and the overall ripple voltage waveform repeats at twice the AC mains frequency. As the SMPS circuit works at much higher frequency (in the range of 20 kHz) the input voltage, in spite of being uncontrolled, a constant magnitude may be considered during any high frequency cycle. A quick switching device S like a MOSFET or IGBT is applied with fast progressive control over switch duty ratio (ratio of ON time to switching time-period) to sustain the expected output voltage. The transformer, in Fig. 2.2, is used for voltage isolation as well as for better matching between input and output voltage and current requirements. In order to achieve a good coupling primary and secondary windings of the transformer are wound so that they are linked by nearly same magnetic flux. The output portion of the fly-back transformer consisting of voltage rectification and filtering is relatively simpler than in most other switched mode power supply circuits. According to the circuit, the secondary winding voltage is rectified and filtered simply applying a diode and a capacitor. The voltage drawn across this filter capacitor is the SMPS output voltage.

The advantage of a fly-back transformer design is that the output voltage multiplication can be very high with short duty cycles which makes this topology ideal for high output voltage power supplies. Another advantage is that multiple outputs (with different polarities if required) can be easily implemented by adding multiple secondary windings for generating multiple isolated voltages. The component count is also very low, so this topology is good for low cost designs. The disadvantage is that the transformer core needs careful selection. Even in the presence of average positive DC current flowing through the transformer, the air-gap core should not get saturated so that efficiency may be reduced due to large magnetic hysteresis. Also eddy current losses in the windings can be a problem due to the high peak currents. These two effects limit the practical operational frequency range of this topology. Finally, the large inductive spike on the primary winding when switch is turned off places a large voltage stress on the switching MOSFET. A more practical circuit will have provisions for output voltage and current feedback and a controller for modulating the duty ratio of the switch [17].

Shortcomings in fly-back DC-DC converter

When the switch S is off as shown in Fig. 2.2, the transformer winding will get saturated owing to DC component current building up in the transformer core. As a result, transformer winding may get damaged by burning due to excessive heat. To overcome this problem, a snubber circuit is required to dissipate the energy stored in the leakage inductance of the primary winding when switch S is turned off. However, power loss in the snubber circuit reduces the overall efficiency of the fly back type SMPS circuit. A typical figure for efficiency of a fly-back circuit is around 65-75%. As a whole snubber capacitor does not remove any portion of energy deposited in the mutual flux of the windings, the least consistent state snubber capacitor voltage should be more than the reflected secondary voltage on the primary side. This can be achieved by proper choice of the snubber resistor and by keeping the RC time constant of the snubber circuit significantly higher than the switching time period. Since the snubber capacitor voltage is maintained higher than the reflected secondary voltage, the most pessimistic switch voltage stress will be the sum of input voltage and the peak.

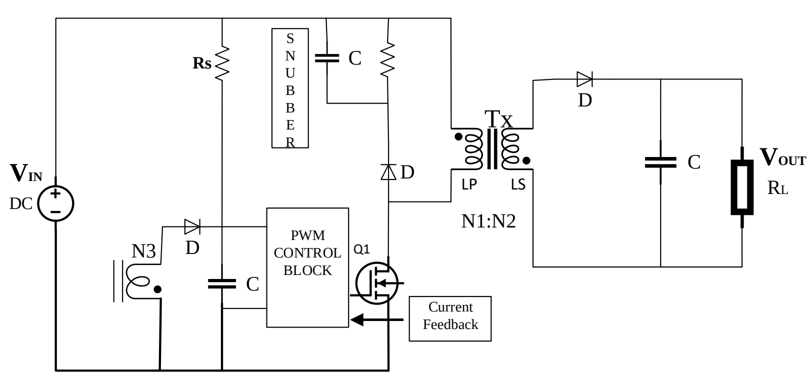


Fig. 2.3: Practical fly-back DC-DC converter. [18]

The circuit in Fig.2.3 also shows, in block diagram, a PWM control circuit to control the duty ratio of the switch. In real fly-back circuits, one needs to feed output voltage magnitude to the PWM controller for closed loop output voltage regulation. The output voltage signal needs to be isolated before feeding back for maintaining ohmic isolation between the output voltage and the input switching circuit. In this type of converter tertiary winding is used for feeding the isolated voltage information to the PWM controller. The method for rectifying the tertiary winding voltage is as similar as the rectification performed for the secondary winding. The rectified tertiary voltage will be somewhat proportional to the secondary voltage multiplied by the turns-ratio between the windings.

2.3.2 Forward DC to DC converter

Transformer will be required by this converter to send the energy, between the input and output in a single step. Although the forward converter seems similar to the fly-back topology, it functions in a completely different way. The input voltage is now turned into a controlled output voltage as a function of the turns ratio of the transformer. Energy keeps on propagating continuously via transformer action by a forward converter from primary to secondary rather than storing packets of energy in the transformer core gap which is dissimilar to the fly back converter, thus no air gap is required for core with its associated losses and radiated EMI. As hysteresis losses are not so critical the core can also have a greater inductance. The winding and diode losses are reduced due to declined peak current and lead to a lower input and output ripple current. The same output power will lead to introduce a more efficient forward converter. In order to maintain smooth operation, component cost will be higher and a minimum load requirement to stop the converter going into the discontinuous mode with a corresponding drastic change in the transfer function.

2.4 Different types of LED driver topologies

LED driver circuits are mainly classified into three categories according to their circuit structures. They are single-stage LED drivers, two-stage LED drivers and integrated stage LED drivers. In the following sections, their characteristics, targeted power levels, and applications will be analyzed briefly.

2.4.1 Single-stage LED driver

Fig 2.4 shows the block diagram of single-stage LED drivers which contain only PFC pre-regulator to regulate the average LED current and achieve high pf simultaneously. This type of driver circuit will be compact, low component count, and low cost. Usually, single-stage LED drivers should be capable of providing high voltage step-down ratios for low LED string voltage, which makes transformer-isolated PFC pre-regulators to be good candidates for single-stage LED drivers. In order to further lower the cost and complexity of controller, discontinuous-conduction mode (DCM) is preferable since high power factor can be automatically achieved by the converter with mixed switching frequency and duty cycle. In comparison with other driver categories, this type of LED driver is advantageous to efficiency due to the use of single power processing stage. However, the conversion loss incurred by the transformer and other components remains an obstacle to achieve high efficiency.

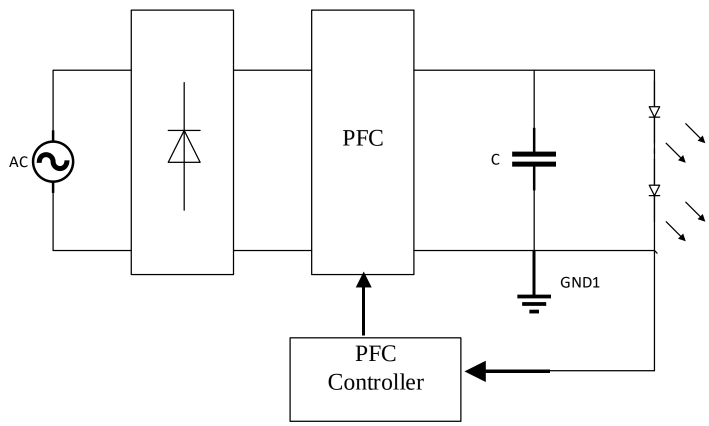


Fig 2.4: Block diagram of single-stage LED drivers. [15]

One of the examples of single-stage LED driver topology is fly-back LED driver for low component costs and high efficiency. Fly-back SMPS is proven to deliver high power efficiency at low-cost fly-back topology as shown in Fig 2.5 has a simple design suitable for low power applications. The fly-back transformer serves as an energy storage medium, as well as providing galvanic isolation in practical application, and simplifying design.

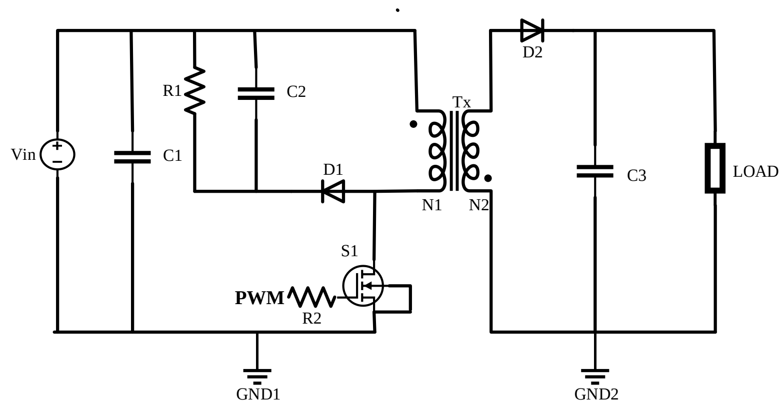


Fig.2.5: Basic fly-back circuit. [18]

They deposit energy in their power transformer during their power transistor on time while load current is supplied from an output filter capacitor. The energy gets deposited in the power transformer is transferred to the output as load current and to the filter capacitor to replenish the charge when it was delivering load current. The entire process is carried out when the power transistor remains switched off. The major advantage of this topology is that the output filter inductors required for all forward topologies are not required for fly-backs. Specially for multi-output power supplies, this is a remarkable saving in terms of cost and space.

2.4.2 Two-stage LED driver

Fig 2.6 shows the block diagram of two-stage LED drivers which are typically found in existing LED drivers. They comprise a PFC voltage pre-regulator followed by an DC/DC current regulator or a resonant converter such that PFC and output current regulation are implemented independently by dedicated controllers. The overall driver efficiency of two-stage LED drivers is generally lower than single-stage LED drivers due to repeated power processing by two stages. Although this LED driver structure involves higher component count, it can render more functionalities by the downstream circuitry, such as fast PWM dimming or low-frequency ripple attenuation. The combination of the PFC voltage pre-regulator and the downstream circuitry can vary with design and output requirements. In this type of driver component count would be more and expensive in comparison with single stage driver [15].

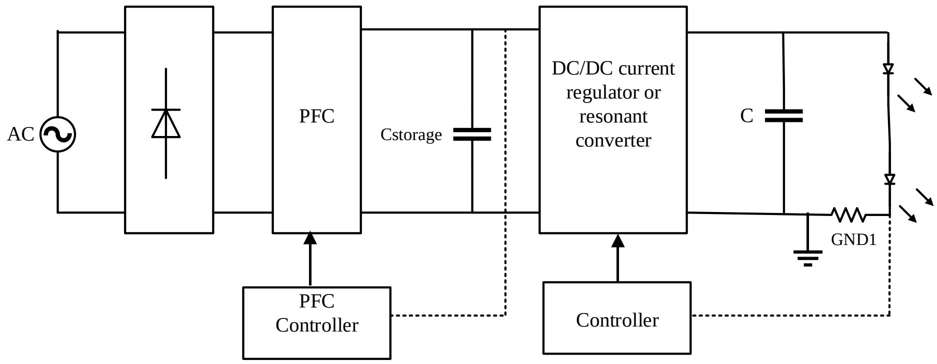


Fig. 2.6: Block diagram of two-stage LED drivers. [15]

2.4.3 Integrated LED drivers

Fig 2.7 shows the block diagram of integrated LED drivers which in fact originate from two-stage LED drivers. By sharing the active switches of the PFC stage and the DC/DC converter stage, the number of components and cost can be reduced. However, since the converters have to achieve PFC and output current regulation with a single controllable switch, the performances are mutually affected. Moreover, even though the appearance is similar to single-stage LED drivers, the input power is still processed twice. Therefore, the PFC and DC to DC converter cells should be designed carefully for achieving high efficiency. Because of the interdependence between the PFC stage and the DC/DC converter stage, there is a trade-off between the performances of power factor and tight output current regulation. In other words, the limitations of integrated LED drivers are inherited from single-stage LED drivers.

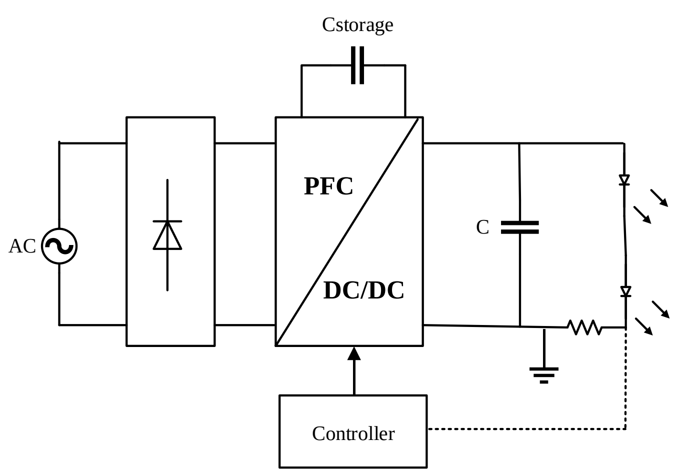


Fig. 2.7: Block diagram of integrated stage LED drivers. [15]

2.5 PWM regulation techniques

There are two basic types of PWM control. One control technique is voltage control (voltage mode). In which the duty ratio D is proportional to the error difference between the actual and a reference voltage. In the current control (current mode) the duty ratio D is the proportional to the deviation from a reference voltage and a voltage related to a current, which may either be the current through the power switch in non-isolated topologies or the primary current in isolated converters. A constant voltage regulator is responsive only to changes in the load voltage and adjusts the duty cycle accordingly. As it does not directly measure load current or input voltage, it must wait for a corresponding effect on the load voltage with any changes in the load current or input voltage. This delay affects the control characteristics of the switching regulator so that there are always several clock periods required for stabilization. The control loop must therefore be compensated to avoid overshoot or output voltage instability. Fig. 2.8 shows a typical voltage-mode PWM controller. The advantages of voltage mode control are single feedback loop, good noise margin, low impedance output and fixed switching frequency, however, few disadvantages are slow dynamic response, double pole compensation and output capacitor effect on the comparator.

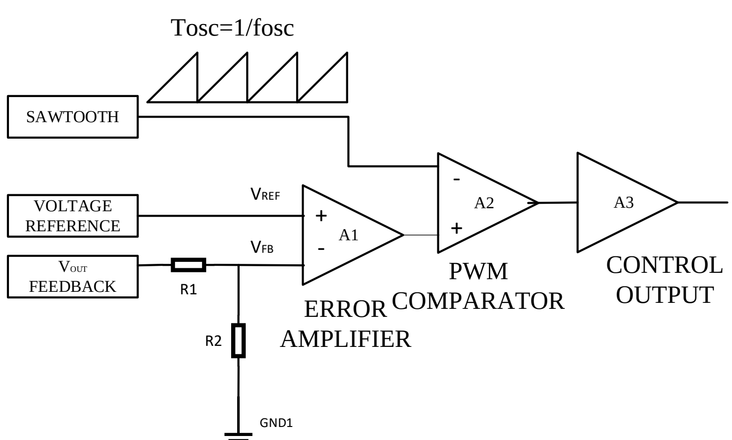


Fig. 2.8: Block Diagram of a Voltage-Mode PWM Controller. [18]

If quick response of the PWM control is required to reduce the reaction time for a step response (transient response), then the alternative current control (Current Mode Control) can be used to eliminate this drawback. In switching regulators with current-mode control, two control loops exist: an inner loop regulating the current in the switch and inductive storage element, and an outer loop which conventionally regulates the output voltage with regard to the internal reference voltage. It is essential to note that the control circuits run at different speeds: the current control loop reacting pulse by pulse, the voltage control loop running much slower to give an output voltage that is stable over time. Fig. 2.9 shows the block diagram of current mode control.

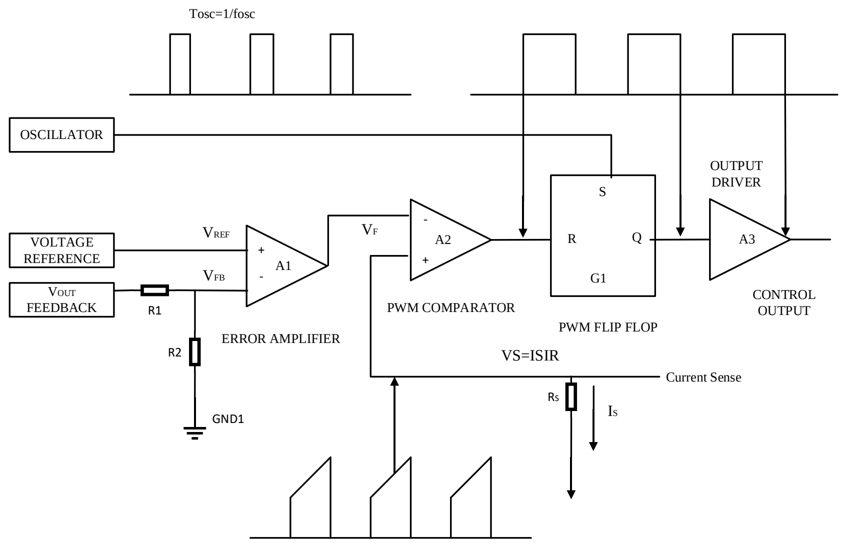


Fig. 2.9: Block diagram of a Current-Mode PWM Controller. [18]

The advantages of current mode control are fast response to input voltage changes, single-pole compensation, inherent current limiting and parallel-ability with load sharing, however, few disadvantages are two feedback loops and need for slope compensation [17]. It also requires blanking to address sensitivity to current spikes.

2.6 Multi-channel LED driver

Major challenges for multistring LED driver are explained in chapter 1. Different control schemes are invented to address these problems so that current balancing for each LED string can be achieved. However each model of current balancing method has merits and demerits. There are proposals which are discussed with number of solutions for operating multi-string LED systems with independent current control. They can be broadly classified into two types, as shown in Fig. 2.10. Their major difference lies in the circuit architecture of the AC/DC stage, which is required to enable an AC voltage input and/or perform PFC function. Fig. 2.10 (a) shows an AC/DC stage which generates a single common output bus V_o that is shared by all the LED strings whereas Fig. 2.10 (b) shows an AC/DC stage which assigns a separate output voltage for each LED string. To acknowledge independent current regulation of each

LED string, the output of the AC/DC pre-regulation stage must be attached with an additional post-regulator for each LED string, which regulates the current of the string to which it is connected. There are generally two types of post-regulators: linear type and DC/DC converter type. The linear type of post-regulators gives the simplest hardware configuration, but might incur severe power loss if improperly designed. On the other hand, the DC/DC converter type of post-regulators is ideally lossless. However, each DC/DC post-regulator introduces additional switches and passive component such as inductor to the system. This inevitably leads to a higher system cost and larger form factor that grows as the number of LED strings increases. Therefore, there is always tradeoff between efficiency and the system's cost and size whenever a post-regulator is used. Another problem with the two-stage configuration is that two sets of controllers (one for the AC/DC stage and the other for the post-regulators) are required, which complicates the system design. Additionally, a two-stage structure requires the use of DC-link capacitor(s) typically electrolytic capacitors. If the DC-link voltage is high, it is hard to select a proper capacitor that has a long lifetime. The use of short lifetime capacitors in the LED drivers reduces the reliability of the LED driver.

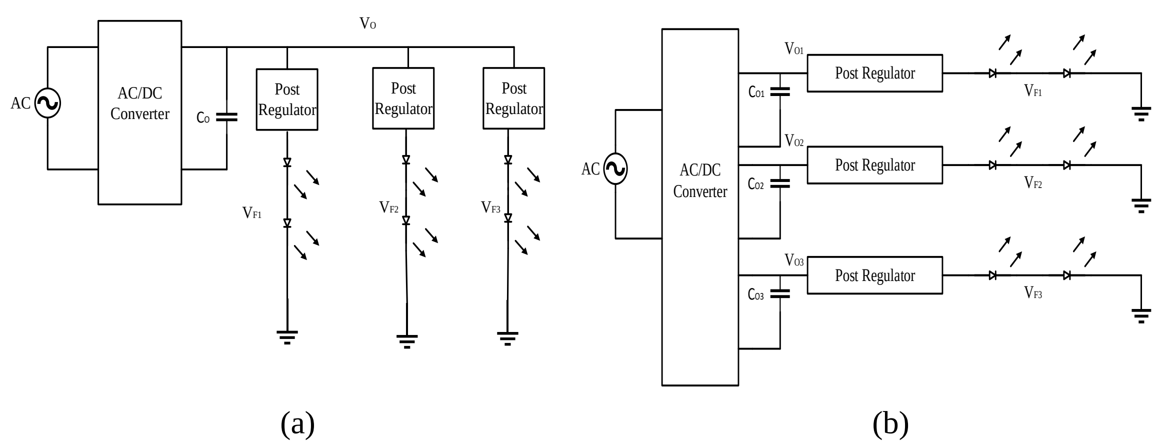


Fig. 2.10. Conventional multi-string LED system of which the AC/DC stage generates (a) a common output bus voltage and (b) a separate output voltage for each individual LED string. [11]

2.7 Multicolor mixing policy

To produce multicolor LED lights by using the single stage LED driver, red, yellow, and blue LED lights will be mixed proportionately. Applying the same feedback circuit for the LED driver, only the current of each LED string will be varied according to the current variations as per color mixing ratio of each color LEDs. In this work, the PWM LED lighting control method will be used where duty cycle in respect of color generation of each LED string will be used. Basically, the total duty cycle will be shared by three colored (red, yellow and blue) LED strings through the programmed look up table. Proportional mixing of LED lights for each LED string would be as per table 2.1 following the color mixing guide [19].

Table 2.1 Proportional Color Mixing Ratio for multicolor LED lights. [19]

Color mixing ratio	Combined mixing color output
2RED+1BLUE	MAGENTA
1RED+1BLUE	VIOLET
2BLUE+1RED	PURPLE
2BLUE+1YELLOW	TEAL
1BLUE+1YELLOW	GREEN
1YELLOW+1RED	ORANGE
1RED+1YELLOW+1BLUE	BLACK
2RED+1BLACK	MAROON
1RED+1YELLOW	PINK
2YELLOW+1BLACK	BROWN

The duty cycle will be shared among the LED strings to generate the above combined color based on the color mixing ratio. Accordingly, the switch will be ON irrespective of the LED string and current will flow through the LED string and emit light from the LED strings. The combined output color will be emitted as per desired. Here in this circuit, the color mixing duty ratio will be controlled through the pre-programmed microcontroller and the switching of each LED string will be done accordingly.

2.8 CCT mixing policy

One of the objectives of this multicolor LED driver is to produce different CCTs of LED street lighting systems so that from a single driver, multiple CCTs can be generated. Usually, two drivers are required to control warm and cool CCT lights to generate cool and warm white lights from LEDs. Here an endeavor has been made to produce a dynamic LED lighting system so that different combined CCT LED white lights with a single LED driver system can be introduced. In this work, two LED strings, comprising warm white (3000K) and cool white (7000K) LED lights are connected in parallel and each LED string will be controlled by a pre-programmed look up table where duty ratio for ON state for each LED string will be stored for the particular desired CCT of the combined LED lights. A non-linear empirical LED model of a bi-color white LED system has been described in [7], where the duty ratio for warm white LED and the duty ratio for cool white LED lights have been set for combined LED lights from both the LED strings. In the same model, the effect of junction temperature, which in turn causes a shift in the color spectrum, and other variations of LED light, are also being considered. The duty ratio irrespective of warm and cool LEDs for combined light for different CCT with luminous intensity is given in table 2.2.

Table 2.2 Duty ratio for cool and warm white LED light strings for different CCTs. [7]

CCT in Kelvin (K)	100 lumen		300 lumen		550 lumen	
	Duty ratio for cool LED (D_c)	Duty ratio for warm LED (D_w)	Duty ratio for cool LED (D_c)	Duty ratio for warm LED (D_w)	Duty ratio for cool LED (D_c)	Duty ratio for warm LED (D_w)
3000	0.02	0.15	0.04	0.44	0.09	0.88
4000	0.04	0.10	0.15	0.31	0.31	0.60
5000	0.08	0.05	0.27	0.18	0.54	0.36
6000	0.10	0.04	0.34	0.12	0.70	0.21
7000	0.12	0.02	0.40	0.05	0.81	0.11

To generate combined 4000 K CCT lights from the proposed driver model, according to non-linear data from the above mentioned table 2.2 cool white LED string needs to be in ON state for 360x0.31=108 degree and warm white LED string to be in ON state for 360x0.6=216 degree for single duty cycle. Both the strings data will be fetched from the pre-programmed look up table. Since the frequency of the ON and OFF states would be very high, flickering effects will not be evident. Once particular combined CCT of LED light is desired automatically data will be fetched from the look up table and the switch of each LED string will be regulated, thereby current is controlled by this process. Switching frequency for both the LED strings will be kept constant.

2.9 Dimming control of LED light

PWM control mechanism will be incorporated for dimming of combined LED lighting system. LED string current will be controlled through this dimming method which will control the average magnitude of supplied current for each LED string. This process is done by dividing each duty cycle effectively into small distinct parts. PWM changes the current supplied to LED strings at high frequency from 0 to the output current rate to regulate the brightness of LED light. The observed brightness of LED light is almost proportional to the pulses duty cycle in terms of output current of each LED string. As current flow through the LED string is proportional to the light output thereby brightness can be controlled through this PWM method. In the proposed brightness control, LED string current was controlled through the feedback circuit current gain ratio. Advantage of PWM dimming is that it enables LED light to be turned off for less time. It will maintain the internal temperature of the LED from rising and potentially develop the operational period of the LED light. Another advantage is color temperature of LED keeps on running at their required amount of electric current with PWM dimming. The projected color temperature of the LED light does not change and remains the same throughout dimming.

2.10 Discussion

The benefits, drawbacks, and applications of various types of DC-DC converters are discussed in this chapter. Non-isolated DC-DC converters have few advantages. However, in the proposed multicolor LED driver, an isolated fly-back DC-DC converter is preferred due to its unique characteristic, which is galvanic isolation from the load and supply voltage. At the same time, the fly-back converter has a few drawbacks, such as the core becoming saturated due to DC current flowing through the primary side of the transformer and the conduction mode being DCM, which may reduce the DC-DC converter's efficiency. However, the core saturation problem has been addressed by designing a proper snubber circuit on the primary side with an optimal selection of component parameters. The merits and demerits of different types of LED driver topologies are discussed, wherein a single-stage LED driver is preferred due to its lower number of components and easy operation. In the proposed LED driver circuit, a rectifier circuit has been incorporated between the supply and the transformer primary side, which will enhance the performance of efficiency and reduce ripple current on the secondary side of the transformer. Different types of PWM methods are discussed with advantages and disadvantages. Finally, the multicolor mixing policy, multi-CCT mixing policy, and dimming control methodology are discussed. In the case of generating multi-CCT non-linear data, the duty ratio has been tabulated in table 2.2.

Chapter 3
Single Stage Fly-back LED Driver

In this chapter, single stage closed loop fly-back LED driver is proposed. Initially, different working modes for single stage LED driver have been described. After that feedback circuit for controlling LED driver circuit has been explained elaborately. The optimal selection of parameters for the proposed constant voltage driver are determined using PSIM software. Therefore, performance indicators for LED driver such as efficiency, power factor and Total Harmonic Distortion (THD) are investigated. Finally, all results are tabulated and showed in different figures.

3.1 Proposed fly-back LED driver

In this thesis, a new constant voltage LED driver topology is testified. The proposed new topology of constant voltage LED driver uses AC-DC fly back rectifier topology. Here single phase secondary winding transformer is used instead of secondary winding transformer with tertiary winding to avoid transformer core saturation due to DC current component in the transformer winding currents. Moreover, a bi-directional switch, with parallel to capacitor and resistor, is used at the primary side of the transformer which works for positive and negative cycle through a combination of inductor and capacitor in order to stabilize the input current and in-phase with the supply voltage. Additionally, the proposed new topology of the single phase AC-DC transformer based rectifier is switched between the AC source and the transformer, instead of switching between the rectifier and the transformer. As a result, the rectification process and DC-DC conversion stands out to be a single stage AC-DC conversion constructing more accurate power factor correction as well as input current harmonic distortion reduction with constant output voltage [20-25].

The proposed circuit for constant voltage LED driver is exhibited in Fig. 3.1 consisting of six diodes (D_1, D_2, D_3, D_4, D_5, and D_6), three capacitors (C_1, C_2, and C_3), one transformer, two switches (S_1 and S_2) and LED lights. The bi-directional switch (S_1) used in the input side operates on both positive and negative cycles. Since input supply voltage is AC, conversion on both cycles is necessary, and it is achieved by the bi-directional switch S_1. A parallel R-C circuit is connected in parallel with bi-directional switch based controlled rectifier which provides path on both positive and negative cycle when the switch is turned off.

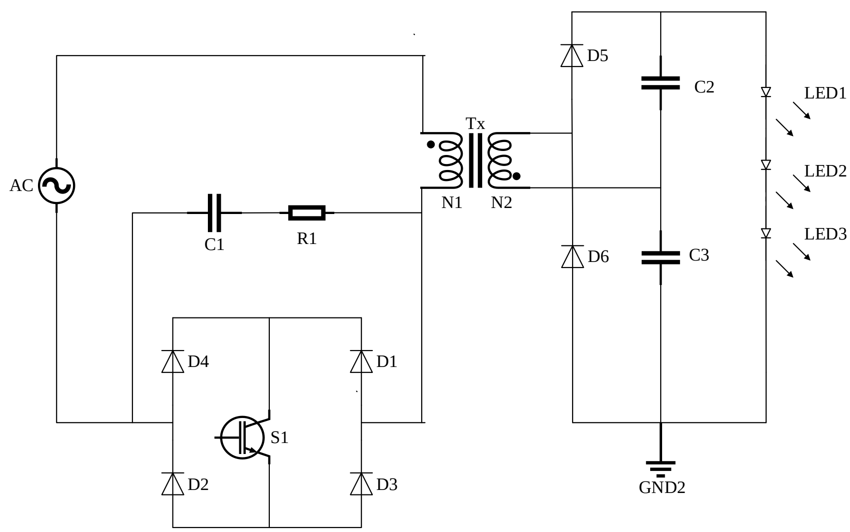


Fig. 3.1: Proposed Fly back LED driver.

3.2 Circuit operating principles

The proposed driver has four states based on ON-OFF of the switch S_1 during positive and negative half cycle of the supply. These four conditions are displayed in Fig. 3.2 along with the direction of current flow. Mode 1 and 2 work on positive half cycle while mode 3 and 4 work on the negative half cycle. The working principle of the proposed driver circuit is described below.

Mode 1: Fig. 3.2 (a) shows the flow of current through the transformer's primary winding during switch S_1 ON period (in positive half cycle). The transformer's primary winding gets energized by the input positive voltage and the current flows in a clockwise direction from Vs to transformer primary winding, switch S_1 and finally returns to Vs. At the same time capacitor C_1 of the primary side which was charged during switch OFF period of negative supply cycle starts discharging in anti-clockwise direction through R_1 and switch S_1. Simultaneously, lower capacitor C_3 of the secondary side which was charged during negative cycle while switch S_1 is turned OFF, now starts discharging through LED lights.

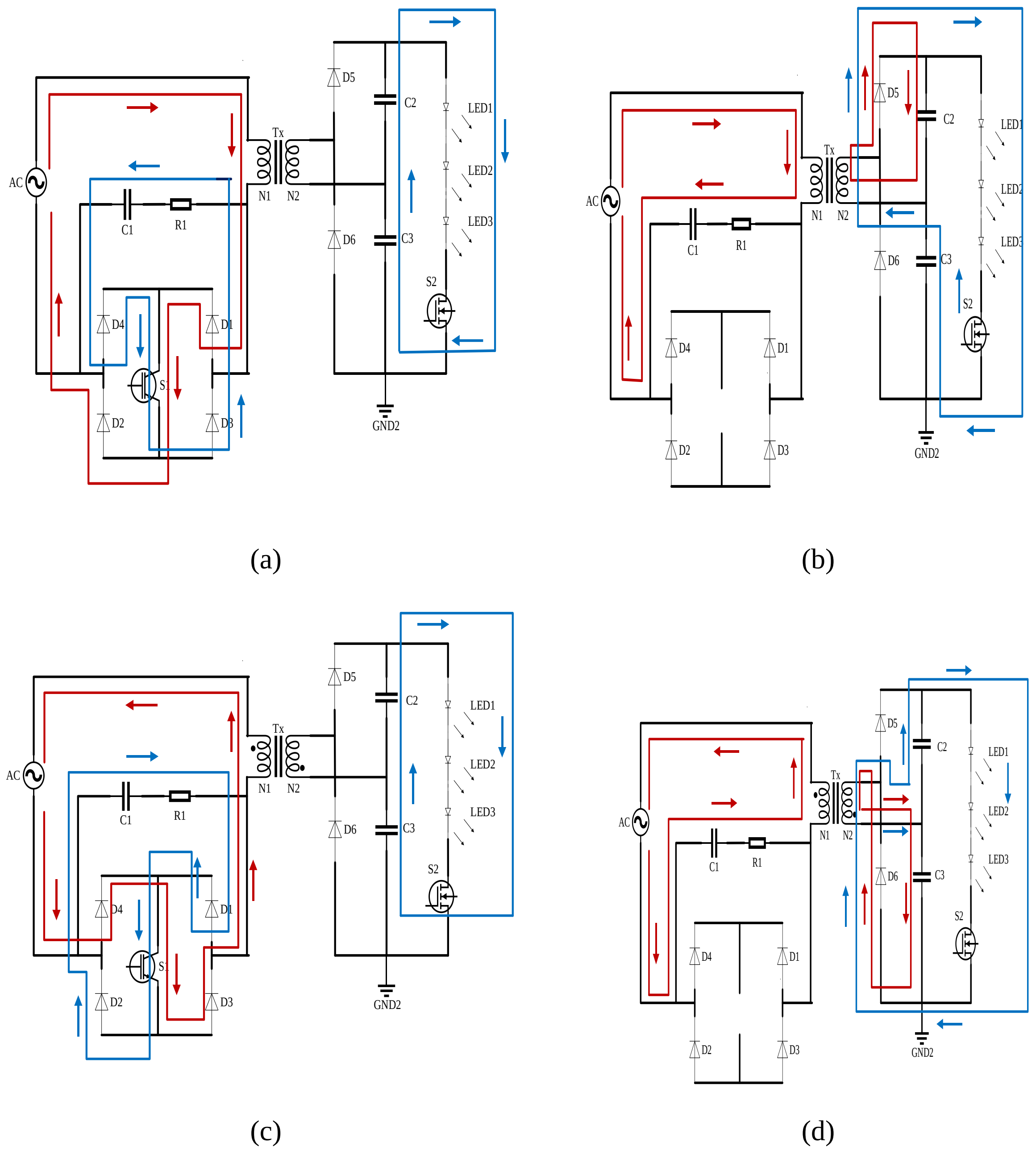


Fig. 3.2**:** Proposed LED Driver's four modes of operation- (a) Mode 1, Switch S_1 ON during positive half cycle of AC supply, (b) Mode 2, Switch S_1 OFF during positive half cycle of AC supply, (c) Mode 3, Switch S_1 ON during negative half cycle of AC supply. (d) Mode 4, Switch S_1 OFF during negative half cycle of AC supply.

Mode 2: During the positive half cycle of the input signal when the switch S_1 is turned OFF, the current from input voltage Vs passes through the transformer primary winding as shown in Fig. 3.2 (b). This time AC current flows in clockwise direction from Vs to transformer's inductor, then resistor R_1 and capacitor C_1 which finally returns to supply voltage Vs. As a result, the AC current flowing through the capacitor C_1 and charges it. In this mode, the secondary side of the transformer current flowing from the secondary winding charges the upper capacitor C_2, whereas lower capacitor C_3 discharges through LED lights.

Mode 3*:* In the negative cycle of the input signal when the switch S_1 is kept ON, the current flowing from the input source Vs follows an anti-clockwise direction through switch S_1, transformer primary winding and returns to Vs. Concurrently, the capacitor C_1 which was charged during switch OFF period of positive supply cycle starts discharging in clockwise direction through R_1 and switch S_1. Whereas in the secondary side of transformer upper capacitor C_2 discharges its stored energy to the LED lights as shown in Fig. 3.2 (c).

Mode 4: When the switch S_1 is turned OFF, the AC current from input voltage Vs passes through transformer primary as shown in Fig. 3.2 (d). In this mode, current flows in anti-clockwise direction from source Vs to resistor R_1, capacitor C_1, transformer's primary winding which finally returns to Vs. In this mode, lower capacitor C_3 at the secondary side is charged whereas upper capacitor C_2 discharges its stored energy to the LED lights.

3.3 Feedback circuit for proposed fly-back LED driver

PFC feedback control circuit is mandatory to improve power factor and to draw the sinusoidal current from the input side. In this proposed LED driver circuit PFC improves the input power factor. Basically, it controls the duty ratio of the input switch S_1 thereby it balances the input capacitor current resulting total input current in phase with the supply voltage as well as it reduces the total harmonic distortion considerably. PFC feedback control consists of two control loops: voltage control loop and current control loop. Based on the voltage and inner current loop, a new type of PFC controller was designed as shown in Fig. 3.3 which in incorporated with the proposed LED driver.

In this thesis, this new type of PFC controller feedback topology will be integrated as PFC feedback control circuit [26-27]. In the proposed new type feedback controller circuit, output voltage is directly connected to the input voltage with a proportional integrator (PI), and output voltage acts as a voltage feedback. Each controller's voltage and current control loop consist of PI controller circuit, and comparing with reference voltage and output voltage generates an error voltage. Generated error voltage then passes through the voltage control PI loop and produces reference current signal for the comparator which has to be compared with the input current, produces an error current signal. After that, error current signal goes through the current control PI loop where output is connected to the comparator of the high frequency carrier signal. Finally, comparing these two signals, the modulated output is produced which operates as the gate pulse for switch S_1 of the driver circuit.

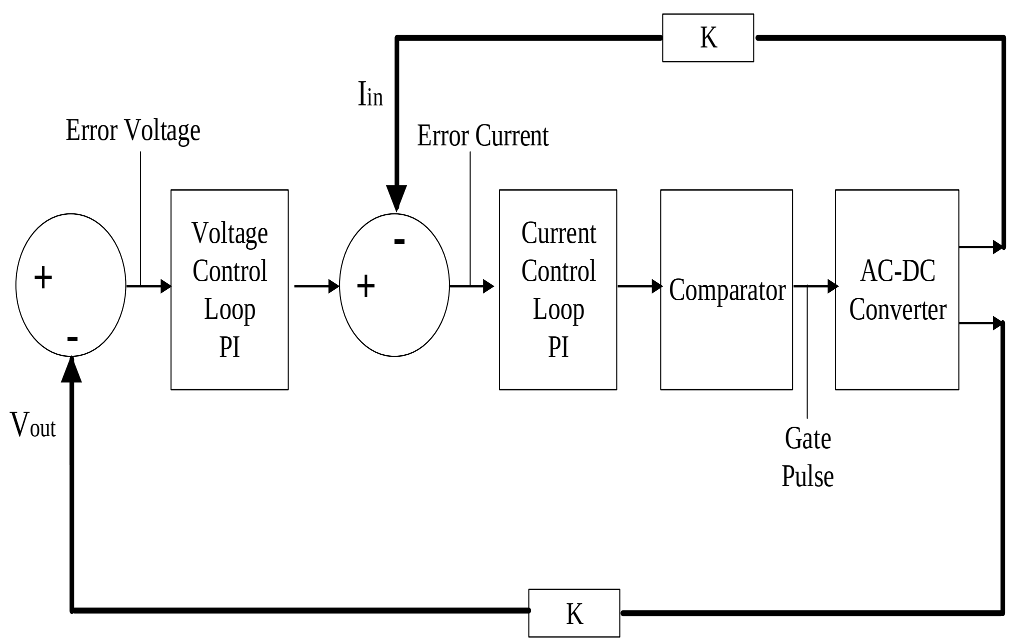


Fig. 3.3**:** Block diagram of PFC control feedback circuit of LED driver. [25-26]

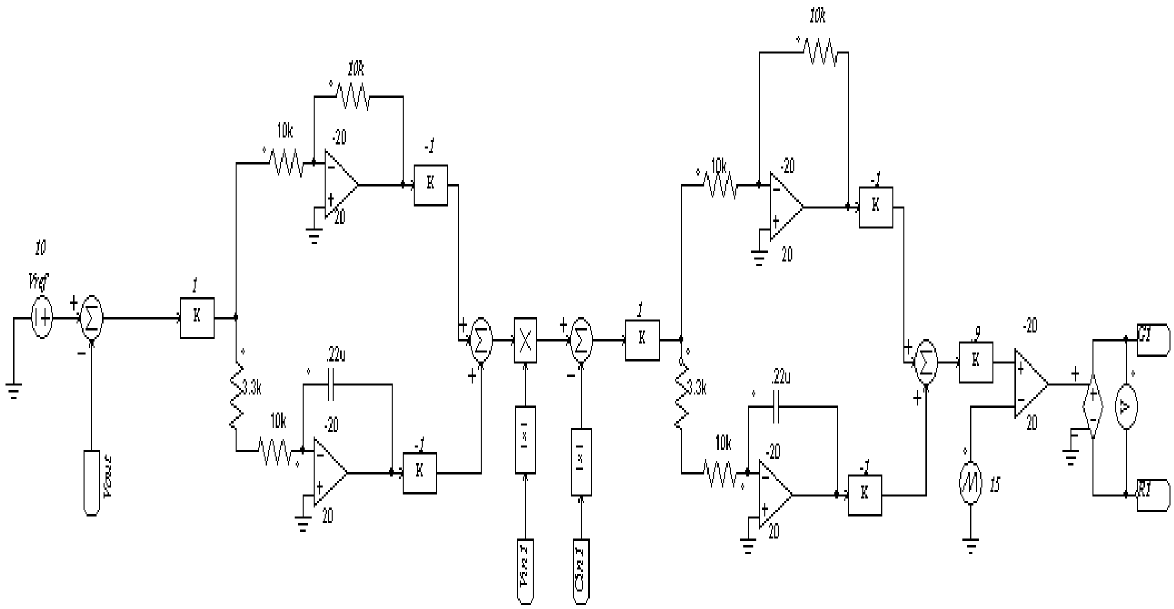


Fig. 3.4: Feedback circuit. [26]

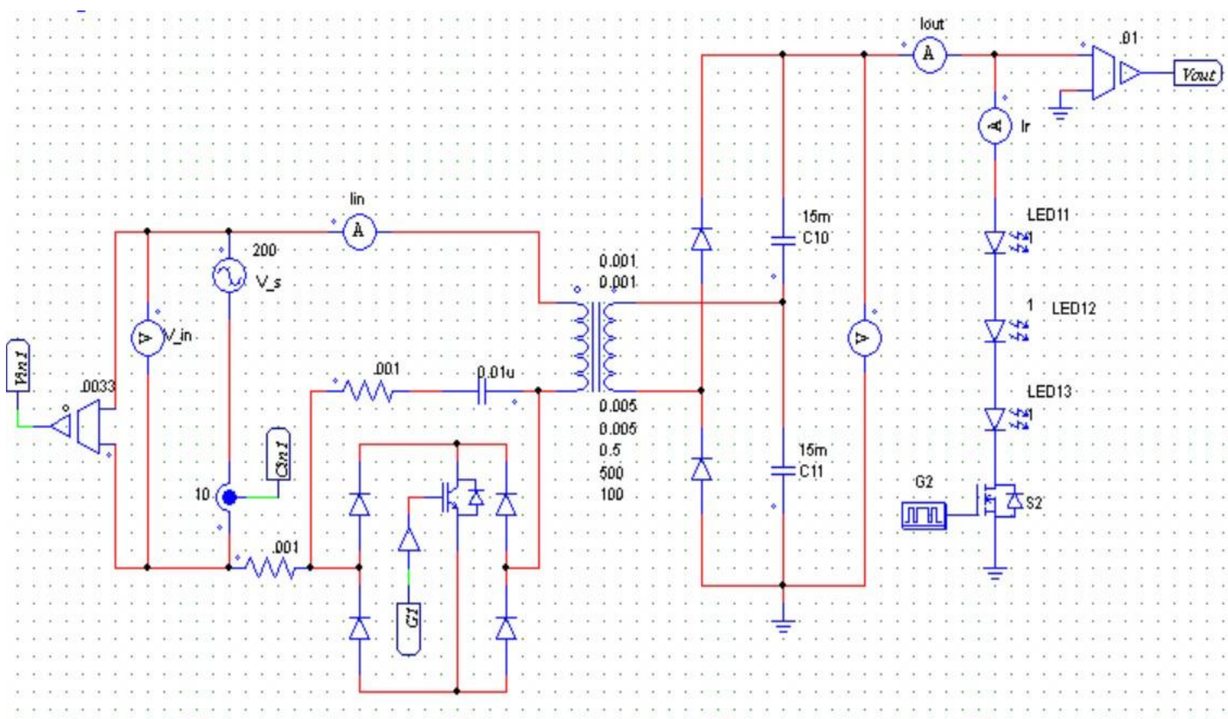


Fig. 3.5: Proposed circuit with current sense resistor.

To measure the input current, either a hall sensor or a current sense resistor may be added in the primary circuit of the proposed driver. The proposed driver circuit simulation was done by adding a current sense resistor as shown in Fig.3.5 and measured the efficiency of the driver (70%). From the simulation, it was found that the efficiency of the driver did not affect by adding a current sense resistor in the driver circuit.

3.4 Experimental parameters for proposed fly-back LED driver

The simulation of the proposed fly-back LED driver of Fig 3.1 is performed with PFC circuit. The values of the circuit parameters are shown in Table 3.1.

Table 3.1: Parameters of the proposed Fly back LED Driver.

Component	Value
R_p(Primary)	0.001 Ω
R_s(Secondary)	0.001 Ω
L_p (Primary Leakage) (Seen from the primary)	1 mH
L_s (Secondary Leakage) (Seen from the primary)	1 mH
L_m (Magnetizing) (Seen from the primary)	500 mH
N_1(Primary)	500
N_2(Secondary)	100
C_2 ,C_3	1mF to 25 mF
R_1	1mΩ
C_1	0.01 μF
LED	Threshold voltage 1V and diode resistance 4Ω
Switching Frequency, S_1	20 KHz
Switching Frequency, S_2	10 KHz

A. Selection of capacitor value

Proposed LED driver was simulated in PSIM software. During the simulation optimal values of the capacitance are determined with several trial experiment keeping load constant and varying the value of reference voltage of the feedback circuit. Preliminary reference voltages at the feedback circuit were considered as 1-25V with 5 volt interval. At the same time with each reference voltage, capacitances of the proposed driver are also varied from 1mF to 25mF. It was found that below 5mF capacitor values output voltage persist large ripple at the output voltage. It was observed also that for reference voltage 10V and capacitance10mF are suitable for the possible acceptable efficiency and THD which are shown in the table 3.2. With these values of capacitor both the deviation and the distortion factors are found to be mitigated in relation to the other values of the capacitors. Subsequent analysis of the proposed LED driver has been done based on the efficiency value greater than 50 percent and input current power factor greater than 80 percent and THD values around 30 percent.

Table 3.2: Selection of capacitor values and reference voltages for the LED driver

C2 and C3	Reference Voltage											
	10V			15V			20V			25V		
	Eff (%)	PF	THD	Eff (%)	PF	THD	Eff (%)	PF	THD	Eff (%)	PF	THD
1mF	85	.905	.472	88	.842	.637	90	.785	.776	91	.778	.794
5mF	56	.933	.303	64	.914	.342	70	.891	.387	70	.887	.387
10mF	54	.929	.313	61	.907	.351	67	.883	.386	68	.879	.386
15mF	53	.928	.316	60	.909	.355	66	.879	.386	67	.876	.387
20mF	52	.927	.317	60	.903	.358	66	.878	.386	66	.875	.387
25mF	52	.927	.315	60	.902	.358	66	.877	.386	66	.874	.388

B. Selection of voltage and current gain of the feedback circuit

Output voltage was observed whether it remains constant or not by changing input voltage with different set of voltage and current gain of the feedback circuit and keeping the reference voltage constant (10V). It is observed that constant 52.63 output voltage is found for the different input voltages (200, 220 and 240 V), different current gains (-0.2 to -0.4), and voltage gains (-15 to -20). For current gain -0.1 and -0.6 and voltage gain ranging from -1 to -10 and -25, it was found variable output voltage with respect to input voltage which are not desirable. For onward same observation were found from other set of values. The results for capacitance values at 10mF, 15mF, 20mF and 25mF for voltage gain -15V, -19V and -20V are shown in table 3.3.

Table 3.3: Selection of Voltage and Current gain of Feedback Circuit for Constant output voltage for proposed LED driver with varying capacitors values with different voltage gain of (a) -15 (b) -19 and (c) -20.

C2 and C3	Current gain											
	-0.2			-0.3			-0.4			-0.5		
	200V	220V	240V	200V	220V	240V	200V	220V	240V	200V	220V	240V
10mF	66.69	66.67	66.67	66.68	66.68	66.67	63.08	66.68	66.68	56.40	60.46	64.33
15mF	66.67	66.67	66.67	66.68	66.67	66.67	62.57	66.68	66.67	56.12	60.17	64.04
20mF	66.67	66.67	66.67	66.67	66.67	66.67	62.30	66.67	66.67	55.96	60.01	63.88
25mF	66.67	66.67	66.67	66.67	66.67	66.67	62.13	66.67	66.67	55.86	59.92	63.79

(a)

C2 and C3	Current gain											
	-0.2			-0.3			-0.4			-0.5		
	200V	220V	240V	200V	220V	240V	200V	220V	240V	200V	220V	240V
10mF	52.64	52.64	52.64	52.63	52.63	52.63	52.63	52.63	52.63	52.63	52.63	52.63
15mF	52.63	52.63	52.63	52.63	52.63	52.63	52.63	52.63	52.63	52.61	52.63	52.63
20mF	52.63	52.63	54.24	52.63	52.63	52.63	52.63	52.63	52.63	52.54	52.63	52.63
25mF	52.64	53.53	52.82	52.63	52.63	52.63	52.63	52.63	52.63	52.48	52.63	52.63

(b)

C2 and C3	Current/ gain											
	-0.2			-0.3			-0.4			-0.5		
	200V	220V	240V	200V	220V	240V	200V	220V	240V	200V	220V	240V
10mF	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00
15mF	50.00	50.00	50.43	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00
20mF	50.00	51.42	50.47	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00
25mF	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00	50.00

(c)

C. Performances of the proposed fly-back LED driver with the selected parameter values

According to previous optimal parameters of input voltage (220V), and voltage and current gain simulation has been done based on varying capacitor values. During simulation efficiency, pf and THD were determined. At voltage gain of -15 in the feedback circuit, efficiency and pf were found acceptable, however, THD was higher (0.5) which is undesirable. Also when voltage gain was -20 efficiency decreased considerably but power factor and THD were found to be good. Therefore, voltage gain was set to -19 where efficiency, power factor and THD were found to be good with constant output voltage which are shown in table 3.4.

Table 3.4: Performance of the proposed fly back LED driver with varying capacitor values at different voltage gain of feedback circuit: (a) -15 (b) -19 and (c) -20.

C2 and C3	Current/ gain											
	-0.2			-0.3			-0.4			-0.5		
	Eff (%)	PF	THD	Eff (%)	PF	THD	Eff (%)	PF	THD	Eff (%)	PF	THD
10mF	80	.803	.523	79	.808	.507	79	.814	.491	70	.862	.416
15mF	80	.792	.521	79	.798	.507	79	.803	.489	70	.857	.416
20mF	80	.786	.521	79	.792	.507	79	.797	.489	70	.855	.416
25mF	80	.783	.521	79	.788	.506	79	.793	.488	69	.853	.416

(a)

C2 and C3	Current/ gain											
	-0.2			-0.3			-0.4			-0.5		
	Eff (%)	PF	THD	Eff (%)	PF	THD	Eff (%)	PF	THD	Eff %)	PF	THD
10mF	71	.873	.436	71	.877	.419	70	.882	.408	62	.914	.338
15mF	71	.865	.436	70	.869	.422	70	.874	.409	61	.912	.340
20mF	71	.861	.437	70	.865	.423	69	.871	.410	61	.909	.341
25mF	71	.858	.437	70	.862	.424	69	.869	.410	61	.907	.342

(b)

C2 and C3	Current/ gain											
	-0.2			-0.3			-0.4			-0.5		
	Eff (%)	PF	THD	Eff (%)	PF	THD	Eff (%)	PF	THD	Eff (%)	PF	THD
10mF	58	.898	.352	58	.904	.338	58	.908	.332	58	.910	.330
15mF	58	.894	.351	58	.900	.339	58	.905	.334	58	.907	.333
20mF	62	.580	.919	58	.899	.340	58	.903	.336	58	.905	.335
25mF	57	.571	.460	57	.898	.340	58	.902	.337	58	.903	.336

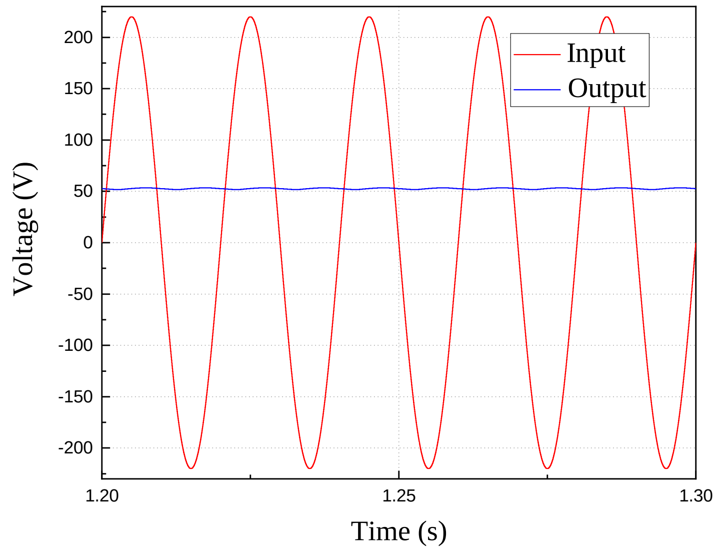
(c)

3.5 Graphical representation of proposed fly-back LED driver

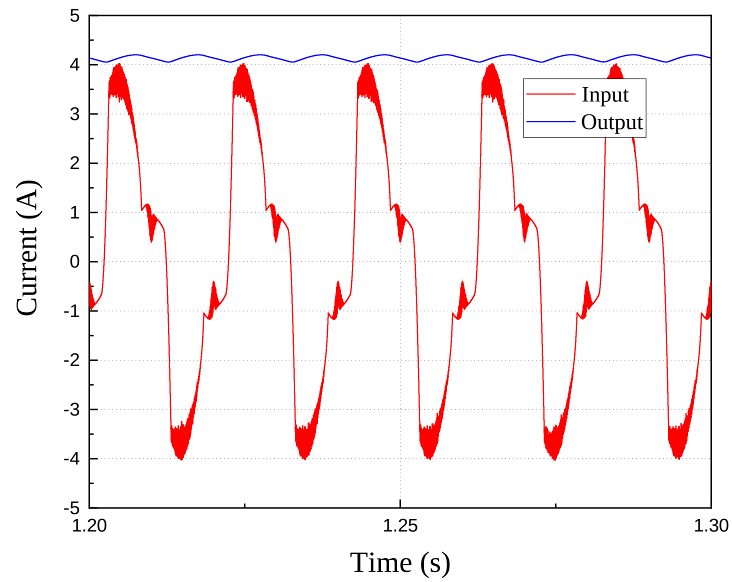
The proposed fly back LED driver with optimal parameters is simulated and different input and output waveforms are presented below.

A. Voltage and current at input and output

In the proposed driver 220V and 50 Hz frequency is considered as input voltage. According to the driver transformer ratio the output voltage was found to be around 52.63V as shown in Fig 3.5(a). Very negligible ripple was observed in the output voltage waveform of the transformer. Accordingly input and output current of the driver was obtained as shown in Fig 3.5(b).



(a)



(b)

Fig 3.6: Input and output waveform (a) voltage (b) current of the proposed driver.

B. Harmonics of the input current

It is observed that there is proportional relation between efficiency and THD input current as shown in the Fig 3.6. However, optimal THD values are considered in relation to power factor and efficiency of the proposed driver. Amplitude at different harmonics of the input current is shown in Fig 3.7 where it is observed that odd harmonics are diminishing.

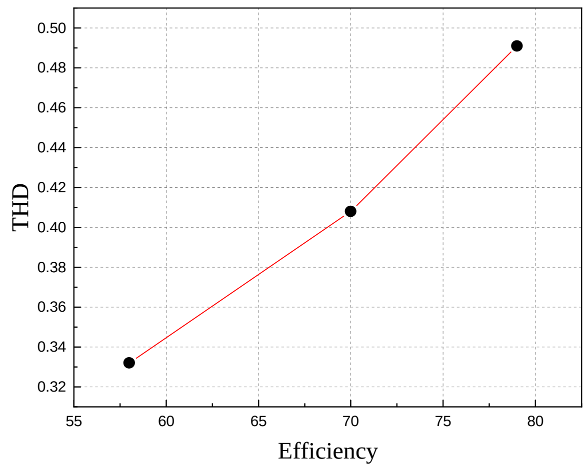


Fig 3.7: THD of current in terms of efficiency.

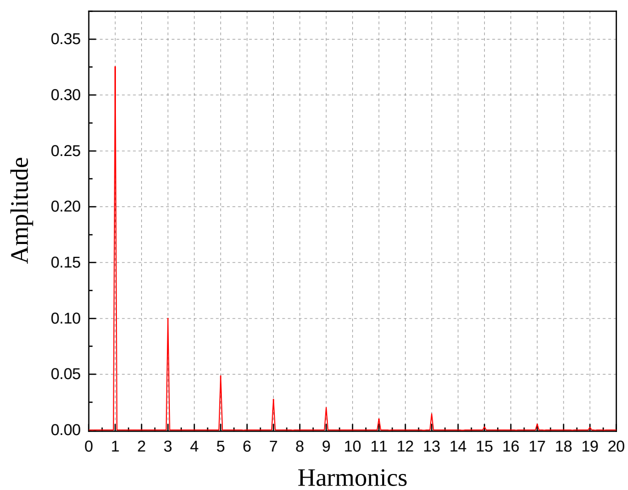


Fig 3.8: FFT of input current.

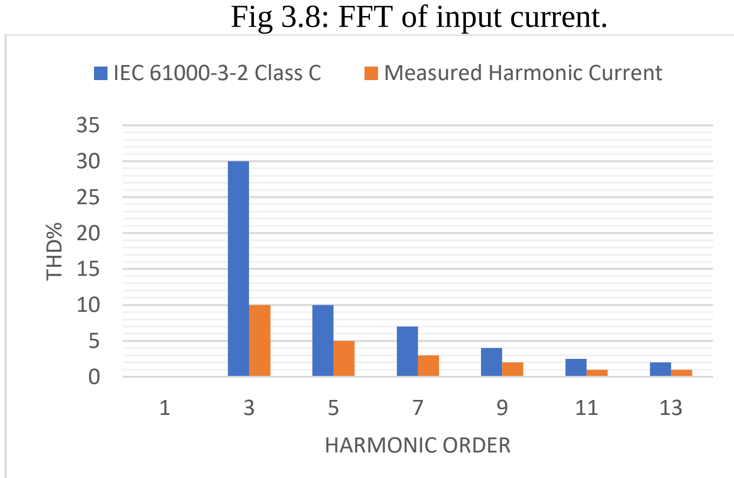
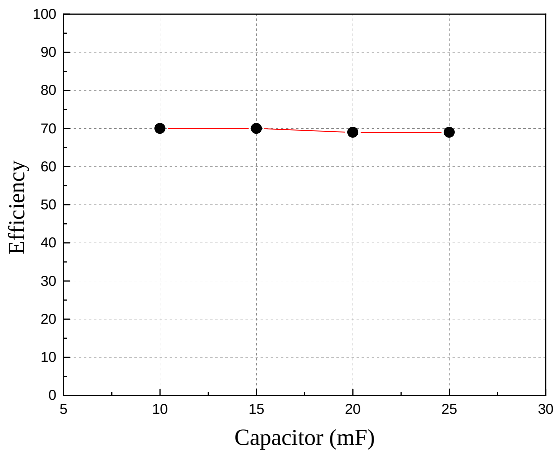


Fig 3.9: Harmonic spectrum of the input line current.

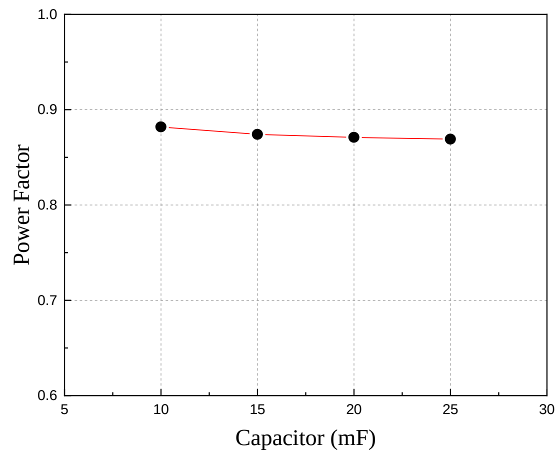
Fig. 3.8 shows the harmonic spectrum of the input current. The THDi was found 40% in the proposed driver circuit and all harmonics are in compliance with the IEC 61000-3-2 Class C.

C. Efficiency, power factor and THD of proposed LED driver

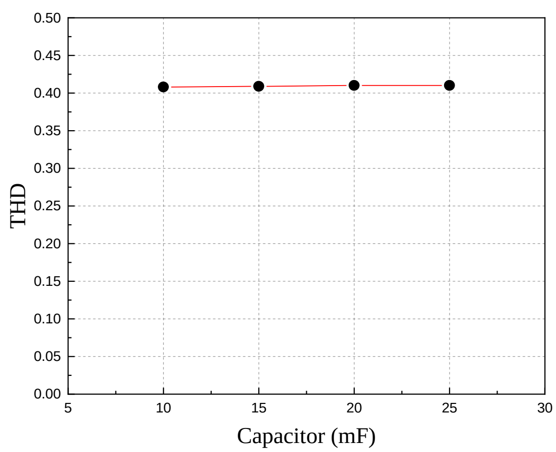
It is interesting to see the robust performance of the proposed driver in terms of efficiency, power factor and THD. The representative efficiency, power factor and THD with respect to the optimal parameters of feedback circuit and Table 3.4 are shown in Fig 3.8 (a), (b) and (c) respectively.



(a)



(b)



(c)

Fig 3.10: Variation of (a) efficiency, (b) pf and (c) THD in terms of capacitor values (for capacitance C_2 and C_3)

3.6 Comparison

The result of the proposed driver is compared with a recent published work [9]. These comparisons are presented in Table 3.5. It is examined that the maximum efficiency of the proposed driver system was found 80%, whereas the overall efficiency of the comparing circuit is 75% and THD is near to the reference circuit but the power factor of the proposed driver was found very less 0.53.

Table 3.5 Comparison between proposed driver with recent work

Factors	**Proposed driver circuit**	**Reff (9)**
Maximum Efficiency (%)	80%	75%
THD (%)	40%	37%
Power Factor (%)	87	53
Component count	less	more

3.7 Discussion

In the proposed single stage fly back LED driver the output voltage is continuously compared with the reference voltages and feedback circuit generates gate pulse for the input switch of the driver. During simulation of the circuit initially it was found large ripple in the output voltage. However, by adjusting capacitor values with other parameters of the feedback circuit, constant output voltage was found with low ripple. In Table 3.4 for the performance of the driver in terms of efficiency, power factor and THD have been tabulated and optimal parameters have been set for the driver and feedback circuit. In Fig 3.5 input and output voltage and current wave shape are shown with feedback and from these figures it is observed that input AC current wave shape is almost sinusoidal and total harmonic distortion is considerably low. However, single input current cycle is analyzed with respect to the feedback gate pulse and it was identified that due to the high frequency switch S_1 (ON and OFF) are the reasons for input current distortion. In Fig 3.7, THD in terms of efficiency is shown where tradeoff between efficiency and THD has been done. Finally, in Fig 3.9 efficiency, power factor and THD for the proposed driver for optimal set of parameters have been shown. However, due to the switch loss, transformer core and copper loss and LEDs resistance, the maximum efficiency of the driver could be achieved 80%.

Chapter 4
Multicolor LED Driver

In this chapter, multicolor LED driver is proposed where red, yellow and blue LED light strings as well as cool white (3000K) and warm white (7000K) LED light strings are combined with the proposed driver. In this driver, red, yellow and blue color LED lights have been mixed to produce desired colors. The microcontroller is used here to control the duty ratio of different color mixing. Applying the same methodology, warm and cool LED lights are also mixed to produce different CCTs of output lights. Timing sequence corresponding to color mixing ratios and CCTs will be explained in this chapter. Finally, dimming of multicolor LED driver has been investigated by changing the current gain of the feedback circuit.

4.1 Multicolor LED driver

Output of proposed constant voltage LED driver is modified by including number of different colors parallel LED strings where current of each LED string is controlled by the microcontroller. Due to the inclusion of switches in each LED string, current can be controlled independently and precisely. Apart from the input feedback for switching control, additionally another control scheme is required to control the output LED string. In this type color mixing methodology different quantities of red, yellow and blue LED lights are mixed proportionately to create a wide range of new colors. It is known that different mixing ratio of red, yellow and blue colors generate different colors [19] [28]. Basically, proposed multicolor LED drivers are used to light up LED string for particular duty ratio in each cycle. Color creation or variation is generated by using the RYB LEDs, each of the LED requires independent control signal for input current amplitude variation. As brightness of a LED linearly depends on the current, a proper drive by controlling amount of current to each LED string should produce a new color following RYB LED mixing ratio. Proportionate current for each string is controlled by the duty ratio of each control switches. Here several colors are considered to be generated by controlling the current amplitude in each LED string. To implement this color mixing, predefined microcontroller is used to generate the PWM signal to each LED string. According to datasheet, the built in PWM module is capable to provide three independent PWM output which can be used for lighting up three independent strings for RYB LEDs. Block diagram of multicolor LED driver is shown in Fig 4.1 where efficiency reaches up to 70% and power factor found 0.88.

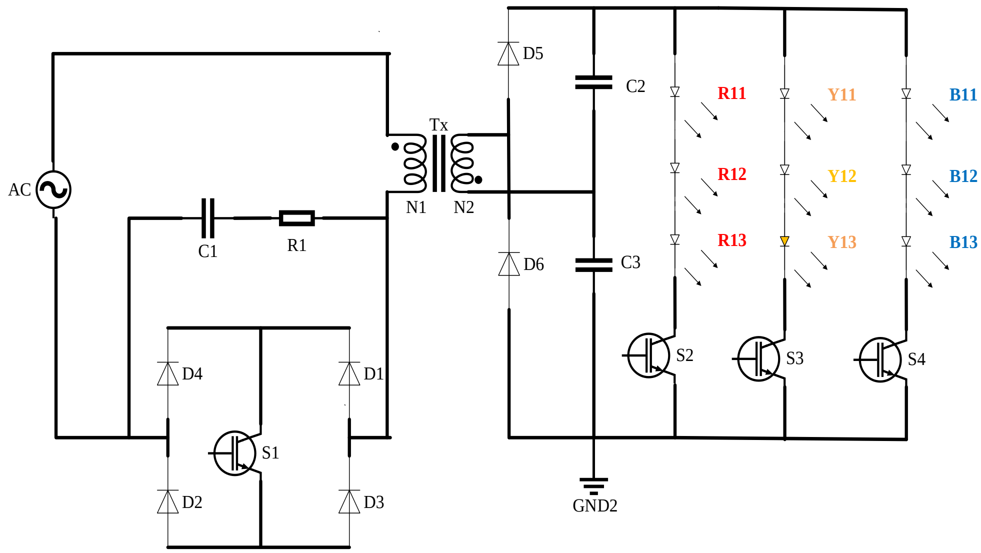


Fig: 4.1 Block diagram of multicolor LED driver.

4.2 Control schemes for multicolor LED driver

In the proposed scheme, multicolor LED driver directly drives multiple LED strings from AC voltage source in a single stage fly back driver topology. A total of three clock generator (G_2, G_3 and G_4) are used to command the output switches (S_2, S_3 and S_4). The current of each LED string is controlled by operating duty ratio of the respective switch. As per the requirement of operating current for each LED string, duty cycle data for each LED string are predetermined and stored in the look up table. One microcontroller is used to fetch the data from the look up table as per requirement and duty cycle ratio is sent to each LED string [7] which are shown in Fig 4.2. Accordingly current will flow each LED string and lit up the LEDs for that particular time. Here three clock generators having the same frequency with different duty ratio will be used to generate output current for each LED string. With different loading condition to each LED string, will have different slopes, duration and amplitude of the output LED current. Thereby, for any instance each LED string output current is controlled by the simple switching technique.

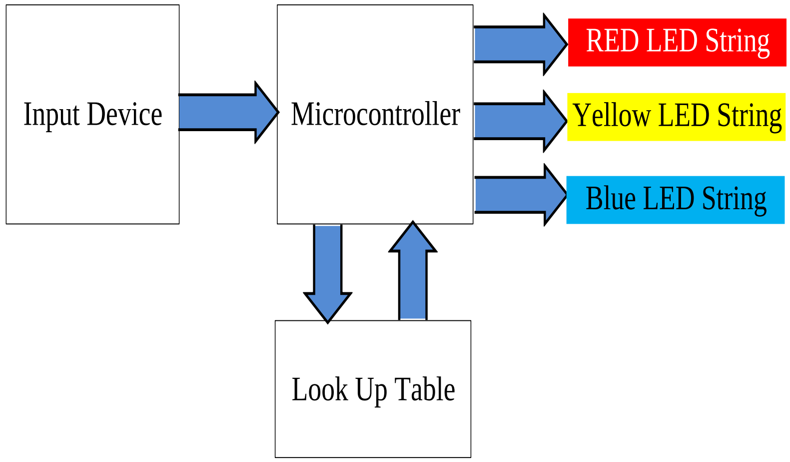


Fig: 4.2 Control scheme of multicolor LED driver.

4.3 Color mixing (Red, Yellow and Blue) methodology

Flow chart of control scheme of the driver is portrayed in Fig 4.3 where control logic register activates the quartz oscillator just after the power is supplied. The frequency of quartz oscillator gets stabilized when the voltage strikes the maximum value and then the procedure of writing bits on SFR (Special Function Register) starts. In the next stage, the program counter is reset to zero address and then the CPU fetches the instruction and decodes it and executes it. After executing the instructions, the program address is increased by one and the next instruction is transferred to the CPU to decode it and execute it. In this work, the lookup table is basically acting as the input which dictates PWM output in the closed loop where V_{out} is the feedback. The duty cycles are mentioned in this look up table which is stored in the memory of the microcontroller and is accessible through the Read Table command. There are three strings in this circuit which combine three different colors of LEDs and the intervals of their emission are set by fixing the duty cycle in the look up table.

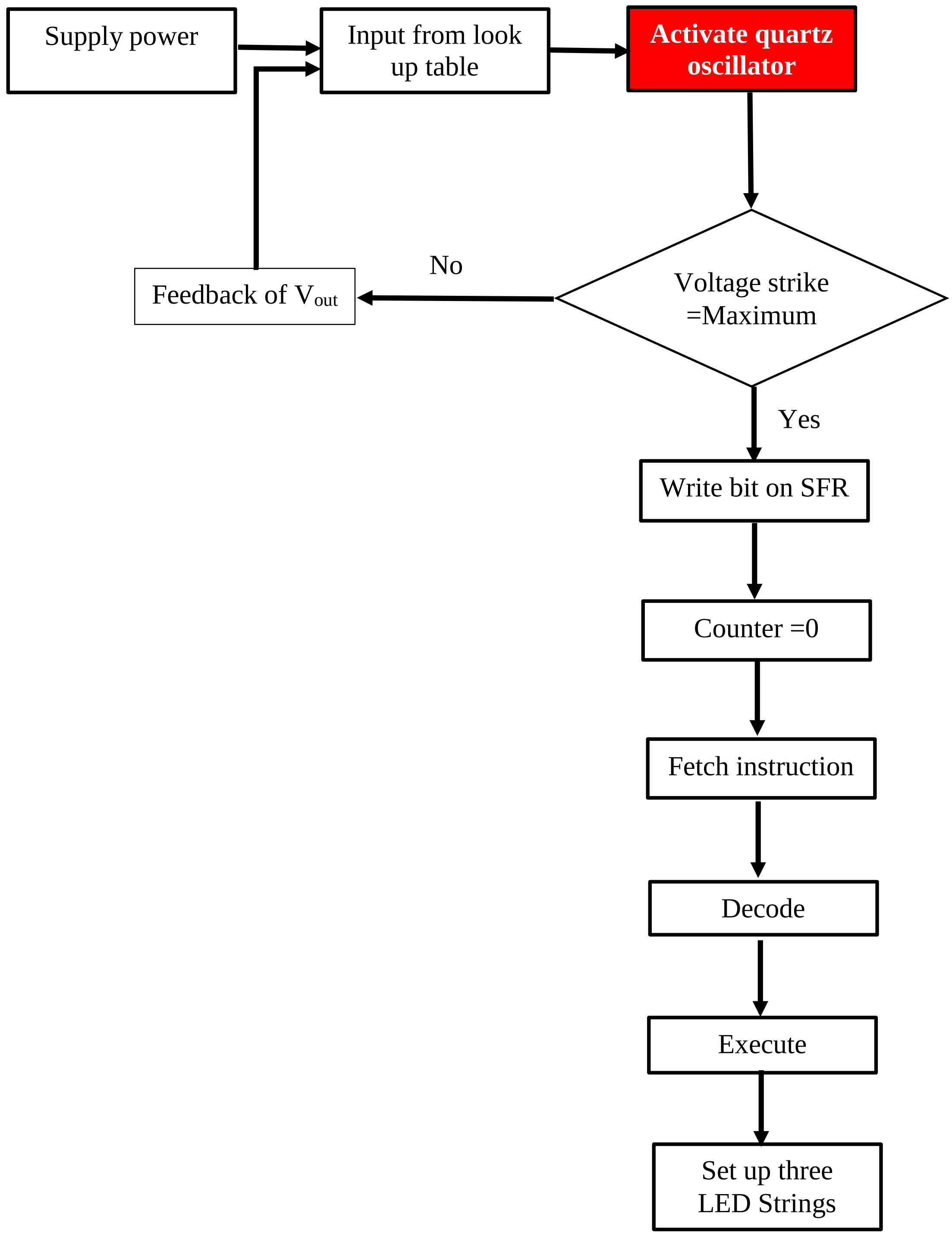


Fig: 4.3 Flow chart of control scheme of multicolor LED driver.

4.4 Results

Here multicolor LED driver is investigated with the help of multicolor mixing control scheme which is responsible to produce different LED color. The function of the control scheme is to generate staggered pulse according to the predefined 360^o landscape from the lookup table. For example if one wishes to generate black color, red yellow and blue LED string should be ON at the rate of 33 percent as shown in Table 4.1. Accordingly current will flow three LED strings and resultant black color will be illuminated as a result of these color mixing. In a similar fashion other colors can be produced using different duty ratio of red, yellow and blue LED string. In table 4.2 desired and achieved color mixing ratio for red, yellow and blue is shown where it clearly depicts that desired color can be achieved from these mixing ratios.

Table 4.1 Duty ratio and string current for different colors.

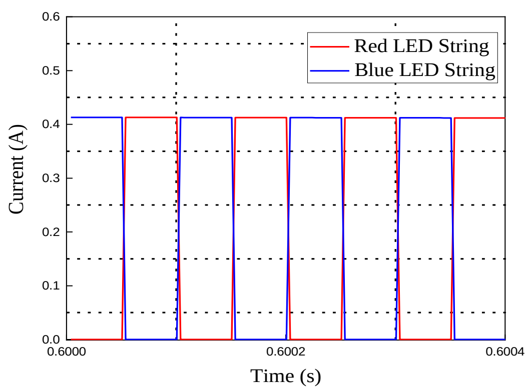
Selected Color	Duty Ratio			Output Current		
	Red	Yellow	Blue	I_r(A)	I_y(A)	I_b(A)
Red	1	0	0	2.970	0	0
Yellow	0	1	0	0	2.970	0
Blue	0	0	1	0	0	2.970
Black	0.33	0.33	0.34	0.965	0.990	1.006
Violet	0.5	0	0.5	1.480	0	1.486
Green	0	0.5	0.5	0	1.480	1.486
Orange	0.5	0.5	0	1.480	1.486	0
Indigo	0.34	0	0.66	0.985	0	1.981
White	0.33	0.17	0.5	0.957	0.521	1.483

Table 4.2 Color mixing ratio desired and achieved for different colors.

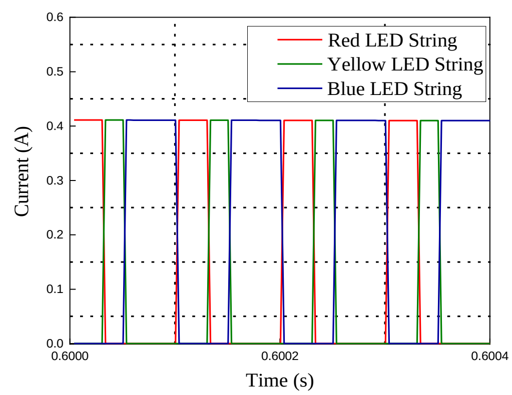
Selected Color	Duty Ratio (Red:Yellow:Blue)	
	Desired	Achieved
Red	1:0:0	1:0:0
Yellow	0:1:0	0:1:0
Blue	0:0:1	0:0:1
Black	1:1:1	1:1:1
Violet	1:0:1	1:0:1
Green	0:1:1	0:1:1
Orange	1:1:0	1:1:0
Indigo	1:0:2	1:0:2
White	2:1:3	2:1:3

A. Timing sequence generation for enabling the color mixing operation

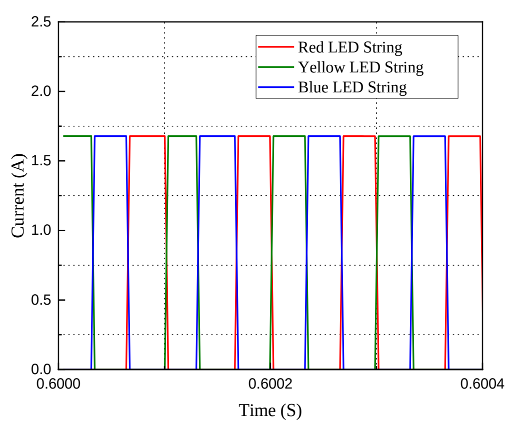
In order to get the timing sequence for the selected color it is necessary to divide the one cycle of the output switching frequency into three parts for three LED strings. According to the color mixing guide [19] different colors are produced by mixing of equal amount and proportional amount of colors. For example, to generate the magenta color the proportional amount of red and blue (2:1) should be mixed. That means red LED string should be ON for a duration of 240^o and blue LED string should be ON for next 120^o (240.1^o to 360^o). Timing sequence generation for black, indigo and white color mixing is shown in Fig 4.4. To generate indigo color (a) R:B=1:1, and for white color (b) R:B:Y=2:1:3. Similarly for black color 4.4(c) proportional amount of R:Y:B should be 1:1:1.



(a)



(b)



(c)

Fig 4.4: Timing sequence of the LED driver for achieving (a) Indigo (b) White (c) Black color.

4.5 Correlated color temperature (CCT) control method

A CCT control system for proposed LED lighting system having two LED light strings with different color temperatures. The LED lighting system has a combined color temperature resulting from the combination of different CCT of the two LED light strings with each LED light string being supplied with a supply current. The CCT control system comprises of a microcontroller to control independently one or both of the duty cycle or amplitude of each supply current being varied by the controller in a non-linear relationship [7]. In this work, the proposed multicolor LED driver is used where two LED strings one warm white CCT (3000K) and another cool white CCT (7000K) LED strings are used as shown in Fig 4.4. In the previous section 4.4, control scheme has been described for color mixture. The same control scheme will be used for this driver. Duty ratio and respective RMS current for cool and warm LED lights for 550 luminous intensity and selected color temperature (CCT) are given in table 4.3 and 4.4 [7][14].

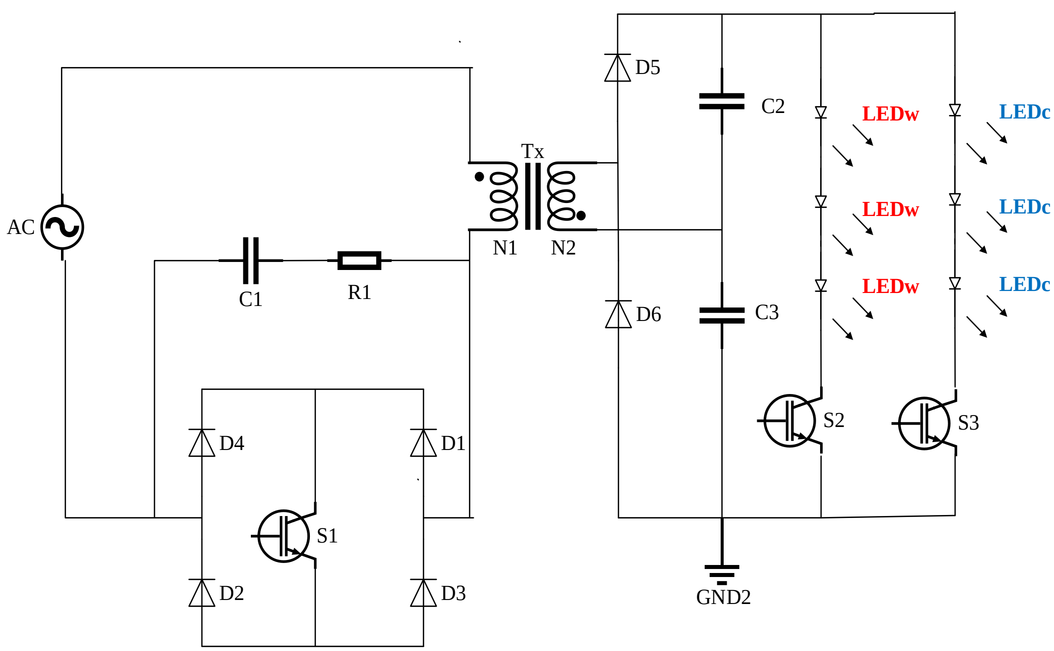


Fig 4.5: Circuit Diagram for different CCTs LED driver.

Table 4.3 Duty ratio for different CCT values [7].

Selected CCT (kelvin)	Duty ratio for cool white LED (Dc)	Duty ratio warm for warm white LED (Dw)
3000	0.09	0.88
4000	0.31	0.60
5000	0.54	0.36
6000	0.70	0.21
7000	0.81	0.11

Table 4.4 RMS current for different CCT values.

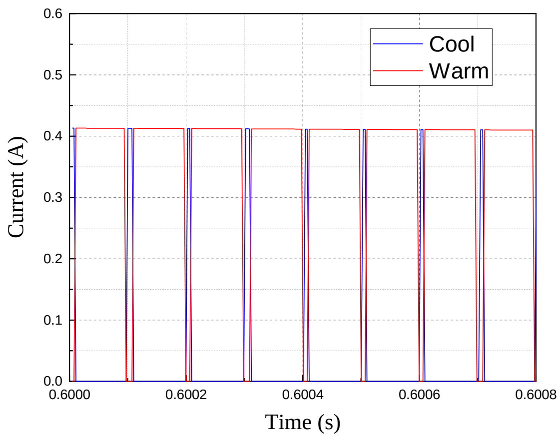
Selected CCT (kelvin)	Cool LED string	Warm LED string	Duty Ratio (Dc:Dw)	
	Ic (A)	Iw (A)	Target	Achieved
3000	0.329	3.637	1:10	1:11
4000	1.244	2.484	1:2	1:2
5000	2.219	1.461	1.5:1	1.5:1
6000	2.854	0.872	3.33:1	3.27:1
7000	3.312	0.449	7.36:1	7.36:1

4.6 Results

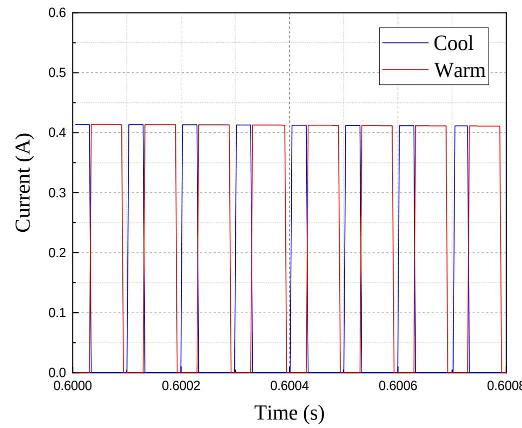
CCT of LED light depends upon the current passes through the LED strings. According to the nonlinear relationship guidelines, duty cycles in proportion to currents are generated as per selected CCT [7]. Once desired current passes through the LED strings, it emits lights proportional to the current. Therefore blending of warm LED string light and cool LED string light takes place and produces a combined CCT of LED lights.

A. Timing sequence generation for enabling the CCT operation

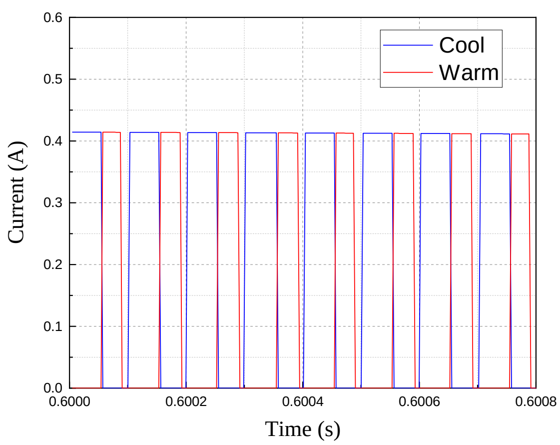
As per Table 4.2 to generate resultant 3000K CCT for LED lights one needs to lit up cool LED string for duty cycle 0.09 which corresponds to 1^{o} to 32^{o} and duty cycle for warm LED string is 0.88 which corresponds to 32.1^{o} to 349^{o} for each cycle. Timing sequence for 3000K is shown in Fig 4.5 (a). Similarly with the variations of duty cycle for each LED strings resultant CCT can be generated and timing sequence is given in Fig 4.5 (b), (c), (d) and (e).



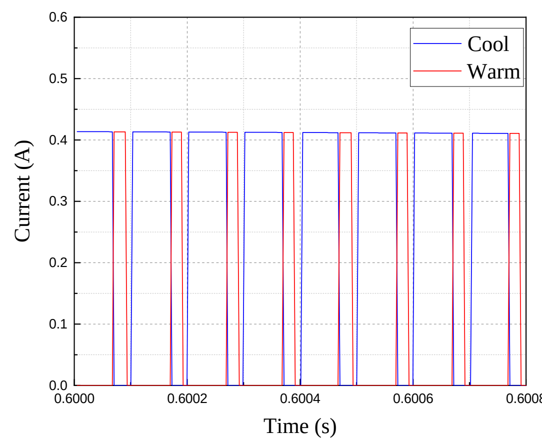
(a)



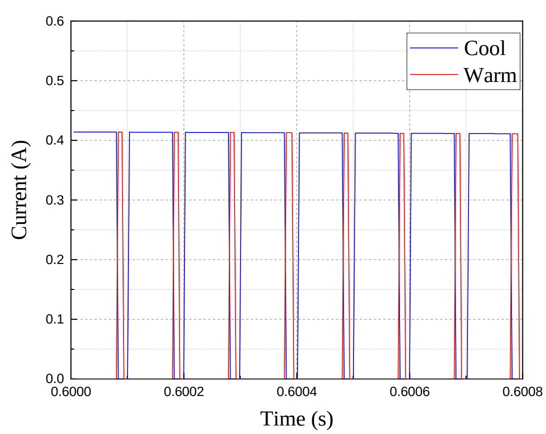
(b)



(c)



(d)



(e)

Fig 4.6: Timing sequence of the LED driver for (a) 3000K (b) 4000K (c) 5000K (d) 6000K, and (e) 7000K CCT values.

4.7 Dimming methodology for multicolor LED driver

Dimming of multicolor LED light was done by controlling the current through different color LED strings. Here basically PWM dimming is adapted. In the proposed feedback circuit, output current of each LED string can be varied by changing the input current gain of the feedback circuit. Therefore, it controls the luminous intensity which is proportional to the current of each LED string. Here combination of white light is considered. From the Table 4.3, it can be concluded that for a current gain of the feedback circuit is -1.0, the brightness level is found to be maximum (100%) and both the targeted and achieved color mixing ratio are same i.e. 2:1:3. When the absolute value of current gain of the feedback circuit is gradually increased, it is observed that brightness of LED lights are decreasing. In case of other color mixing and CCT controlled LED lights' dimming can be done by the same process.

Table 4.5 Dimming control of LED lights with output current control

Current Gain	Brightness level (%)	I_r(A)	I_y(A)	I_b(A)	**Mixing Ratio**	
					Target (R:Y:B)	Found (R:Y:B)
-1.00	100	0.957	0.521	1.487	2:1:3	2:1:3
-1.19	90	0.855	0.472	1.338	2:1:3	2:1:3
-1.35	80	0.761	0.420	1.187	2:1:3	2:1:3
-1.55	70	0.664	0.367	1.035	2:1:3	2:1:3
-1.82	60	0.570	0.312	0.886	2:1:3	2:1:3
-2.13	50	0.482	0.260	0.745	2:1:3	2:1:3
-2.53	40	0.392	0.207	0.596	2:1:3	2:1:3

4.8 Results

To validate the dimming of LED light output white light color mixing LED driver was taken for simulation. Trial run of circuit was done by varying current gain of feedback circuit and it is found that the ratio of red, yellow and blue is similar to that of set values of red, yellow and blue color ratio for white light. It is observed that brightness of LED light is reduced proportionally once the absolute value of current gain is increasing as shown in Fig 4.7. As a matter of fact by changing the current gain of the feedback circuit directly it controls the output current of each LED string which in turns proportionally emit light intensity from the LED strings. In this dimming process microcontroller performs the color mixing of red, yellow and blue color LED strings to produce white light as explained in sec. 4.4.

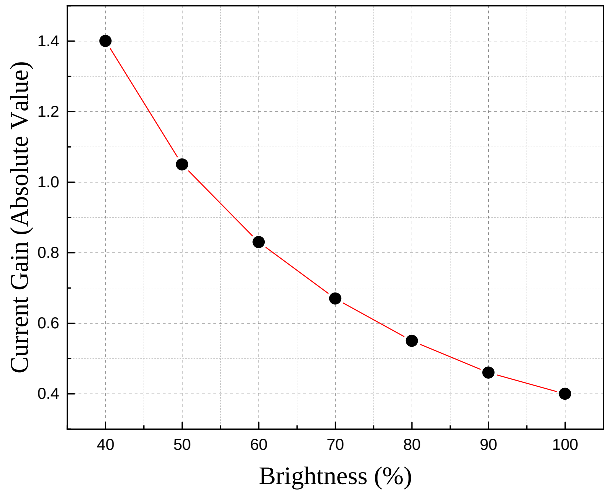


Fig 4.7 Dimming control of multicolor LED driver by varying current gain of feedback circuit

4.9 Comparison

The result of the proposed driver is compared with a recent published work [6]. These comparisons are presented in Table 4.6. It is examined that the efficiency of the proposed system is 71% with single driver whereas the overall efficiency of the comparing circuit is more than 80% with double driver. In the proposed circuit the safety is ensured with isolation where the comparing circuit does not have any. The LED driver of the proposed circuit gets controlled by constant voltage leading to a good noise margin, low impedance output and fixed switching frequencies but the comparing circuit is a constant current controlled driver with no such advantage. The proposed circuit can be applicable for large scale power where the comparing circuit is only applicable for small scale power.

Table 4.6 Comparison between proposed driver with recent work

Factors	**Proposed Fly back Driver**	**Reff [6]**
Maximum Efficiency (%)	80 (%)	80 (%)
Power Factor	0.88	DC-DC conversion so not applicable
THD	40%	DC-DC conversion so not applicable
No. of drivers	1	2
Isolation	Present	Absent
Components	Includes all components	Commercially available driver
Driver Type	Constant voltage LED driver	Constant current LED driver
Application	For large scale power	For small scale power

4.10 Discussion

In the proposed multicolor mixing and CCT control LED driver methodology, the amplitude of the current proportional to luminous intensity of the particular LED string was considered. In order to produce different color, three basic colors red, yellow and blue will be mixed in proportional or equal amount. In case of producing different CCTs of LED lights, warm and cool white LED lights were mixed in non-linear manner. However, in the process of mixing red, yellow and blue colors or mixing warm and cool LED lights, effect of junction temperature of LEDs and ambient temperature variation were not considered in this case. Here the output current amplitude of LED strings was controlled by the microcontroller as per the desired colors & CCTs. In order to achieve dimming of the LED lights, PWM method was considered where the duty cycle of the input signal is controlled by the current gain of the feedback circuit to achieve dimming of the driver.

Chapter 5
Conclusion

This chapter discusses the findings of the research and identifies the scopes of the future work.

5.1 Conclusion

Over the past few years, LED lighting has been emerging as a next-generation lighting technology due to its highly efficient, compact, energy-saving, and environment friendly characteristics. Here a single-stage constant voltage multicolor fly back LED driver was designed. The proposed driver has the capability of producing multi-CCT lighting, mixing, and dimming of light. While designing an LED driver, THD and input power factor are important parameters to be considered in order to achieve maximum efficiency as well as ensure that the main supply line is not affected. Besides, to ensure high input PF and low THD value and control the proposed driver circuit, closed loop feedback is integrated into the overall driver circuit. This driver has better efficiency, input power factor, and low THD value.

In order to construct a constant voltage driver, the proposed circuit was continuously compared with the reference voltage and the feedback circuit generates a gate pulse for the input switch of the driver. In this thesis, PSIM software was used for carrying out different tests and trials of the circuit. During the trial run of the circuit, initially, there was a remarkable ripple in the output voltage. However, by adjusting capacitor values with other parameters of the feedback circuit, a constant output voltage was found with considerable ripple. Finally, the performance of the proposed driver in terms of efficiency, power factor, and THD has been tabulated, and an optimal set of parameters has been set for the driver and feedback circuit. Graphical representation of input and output voltage and current wave shape was portrayed with feedback, and it was observed that the input AC current wave shape was almost sinusoidal and THD was considerably low. However, due to high frequency switching on the primary side of the driver, the input current was having ripples where the switching took place. However, the driver's maximum efficiency could not be increased above 80% due to losses in the switches, the core and copper of the transformer, and the resistance of the LEDs.

With the proposed single-stage fly back LED driver output side, LED strings have been connected in parallel connection. In the proposed multicolor mixing and CCT control LED driver methodology, the amplitude of the current was proportional to the luminous intensity of the particular LED string. In the case of generating multi CCT, two LED strings having a temperature of warm white (3000K) and cool white (7000K) were connected. The duty ratio of these two LED strings is switched as per non-linear data taken from the reference. This proposed LED string data was controlled by a microcontroller and will be saved as a look-up table. Once the desired combined CCT is required, accordingly, look up table data, LED strings will be switched ON and OFF. The output LED string ON and OFF switch frequency would be very high so that it does not have any flickering effect on the output of LED lights. Similarly, multicolor LED lights could be generated by the same model only having three different colors: red, yellow, and blue LED strings. The color mixing ratio has been taken from the ideal color mixing chart. According to the mixing ratio of each color, LED strings would be controlled and generate the desired combined output color. However, in the process of mixing red, yellow, and blue colors or mixing warm and cool white LED lights, the effects of the junction temperature of LEDs and ambient temperature variation were not considered in this case. Simultaneously, in both the models of multi-CCT and multi-color, dimming control is also introduced through feedback circuit current gain variations without distorting the original combined CCT or mixed color output. The PWM method was considered, where the duty cycle of the input signal is controlled by the current gain of the feedback circuit to achieve dimming of the driver. The timing sequence of each model for multi-CCT as well as multi-color combined light output has been portrayed, where there is a clearly visible mixing ratio for both models.

5.2 Future work

From the simulation results, it has been found that the efficiency is degraded under light load conditions, which can be explained by the power loss incurred by the switching devices and transformer losses therefore further study to be carried out to have better performance in terms of efficiency of the proposed driver circuit. The idea has only been validated by the single-stage fly back concept to minimize the volume and loss of overall LED drivers, other LED driver topologies can also be implemented, from which more rigorous and comprehensive comparisons can be made to their counterparts not only on the component count or efficiency but also on the performance of dynamic response in the context of LED driving under the parameter variations. After carried out further study, the proposed single-stage constant voltage fly back LED driver topology may be implemented practically.

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