DESIGN, APPLICATION AND COMPARISON OF SINGLE STAGE FLYBACK AND SEPIC PFC AC/DC CONVERTERS FOR POWER LED LIGHTING APPLICATION

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DESIGN, APPLICATION AND COMPARISON OF SINGLE STAGE FLYBACK AND SEPIC PFC AC/DC CONVERTERS FOR POWER LED LIGHTING APPLICATION

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ABSTRACT

DESIGN, APPLICATION AND COMPARISON OF SINGLE STAGE FLYBACK AND SEPIC PFC AC/DC CONVERTERS FOR POWER LED LIGHTING APPLICATION

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In this work, single stage power factor corrected AC/DC converters for LEDs; single stage Flyback converter having different configuration from the traditional Flyback and single stage SEPIC converter is investigated. The study involves analysis, circuit design, performance comparisons and implementation. The study covers LEDs; their developments, characteristics and state-of-art in this new technology. The circuits are investigated by means of computer simulations. Operating principles and operating modes are studied along with design calculations. After applying prototypes in laboratory, the simulation results and theoretical analyses are confirmed. The single stage Flyback converter has high voltage input (220-240 Vac), and the output feeds up to 216 HB-LEDs, with the ratings of 24 V, 3.25 A with 90 W. The single stage SEPIC converter with universal input (80-265 Vac) has an output that feeds 21 power LEDs, with 67 V, 0.30 and 20 W ratings.

Keywords: Power factor correction, single-stage power supply, LED, LED driver, AC-DC converter

ÖZ

TEK KATLI FLYBACK VE SEPIC GKD'LERİN GÜÇ LED'İYLE AYDINLATMA UYGULAMASI İÇİN TASARIMI GERÇEKLENMESİ VE KARŞILAŞTIRILMASI

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Bu çalışmada Güç LED' i (G-LED) ile aydınlatma uygulaması için güç katsayısı düzeltici AC/DC güç kaynaklarından geleneksel yapıdan farklılık gösteren tek katlı Flyback ve SEPIC devreleri ele alınacaktır. Bu devrelerin analizi, tasarımı, deneysel gerçeklenmesi ve başarımlarının karşılaştırılması yapılacaktır. Çalışma içerisinde LED gelişimi, karakteristik özellikler ve öne çıkan özellikleri detaylandırılmıştır. Çalışmada devreler ayrıntılı bilgisayar benzetimleri ile incelenecek, çalışma ilkeleri ve çalışma kipleri detaylandırılacak, tasarım hesapları yapılacaktır. Çalışmada, söz konusu devrelerin teoriye ve bilgisayarla benzetime dayalı inceleme sonuçları deneysel ilk örneklerin laboratuarda uygulanması ile deneysel sonuçlarla doğrulanacaktır. Çalışmada yüksek gerilim girişli (220-240 Vac) 216 HB-LED sürebilen 24 V, 3.25 A çıkışlı 90 W gücünde tek katlı Flyback devresi ve evrensel girişli (85-265Vac) 21 LED sürebilen 67 V, 0.30 A çıkışlı 20 W tek katlı SEPIC devresi incelenecektir.

Anahtar kelimeler: Güç katsayısı düzeltimi, tek-katlı güç kaynakları, LED, LED sürücü, AC-DC çevirici

To my family and

Memory of my grandfathers,

Hasan Yılmaz and Muzaffer Arıcı

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TABLE OF CONTENTS

CHAPTERS

LIST OF FIGURES

FIGURES

LIST OF TABLES

TABLES

CHAPTER 1

INTRODUCTION

1.1 General

20TH century was the time of inventions and societies adaptation to new energy, electrical power. Developments in industry and growth of populations raised the need for energy sources. However, world has limited capacity to regenerate the sources and pollution affects badly the sustainability of sources. Recently, awareness of the sustainability problems of world, force the governments and committees to develop ways to promote sustainability. In these ways; a key point is energy saving. Energy saving can be succeeded by using electrical power efficiently and properly. In this manner, many technologies are developing in order reduce the consumption.

Worldwide 20% of electric power consumption is for residential, commercial and industrial lighting applications. US consumed 3.747 TWh by the year 2009 which in it lighting has a share of 21 % [1]. By the year 2001, the distribution of light sources was incandescent lamps with 63%, fluorescent lamps with 35%, HID with 2% and Solid-state lamps with 0.08%. Researchers find that the percentage of incandescent lamps in commercial, residential and buildings are still 63%; which is the oldest and poor efficiency technology of lighting. There are ways to save energy for light sources which are categorized in two topics; the developments in new technology and efficiency light sources and the power supply for lighting equipments; the regulations, new technologies and efficiency values. Next section will examine this old technology with its history.

In 1879 Thomas Alva Edison filed for the patent for an electric lamp. Society called this incandescent lamp as “electric lamp” at that time, which is the first man made light source.
Researchers worked to improve the performance, life-time, manufacturing capabilities and cost benefit of incandescent lamps. Now after 133 years, incandescent lamps are still in use. After some improvements efficacy (lumens per watt) values improved to 14 lm/W from 1.4 lm/W of the first Edison’s lamp. This technology was accurate in the manner of usage; it can be used directly with AC power line without a power converter. However, the technology is unsatisfactory in the manner of efficiency. It converts the electrical energy to light with efficiency about 4%.

Companies and scientist developed new light sources with higher efficiency like fluorescent lamps, gas discharge lamps and a new light source as LEDs. The focus of this research is the latest technology; light-emitting-diodes (LED). This forgotten electronic component shows most significant development as its technology of lighting and its wide use area. Today the efficiency of LED is about 15%; in addition, the developments and theoretical statements show that efficiency will rise up to 45%.

LED is a diode that emits light with respect to the current flows through its semiconductor structure. Market calls this new area of this technology for lighting as *solid-state-lighting* (SSL). Power light emitting diodes (P-LEDs) and high-brightness light emitting diodes (HB LEDs) are solid state lighting products typically used over 10 mA. Manufacturers offer P-LEDs by two methods. First method is packaging single pn-junction LED chips on one single package. Second method is assembling multiple packaged LEDs to make LED array.

LED technology achieved high efficacy (lumens/watt). This advantage can be shown by efficacy values of other light sources; incandescent lamp 18 lm/W, fluorescent lamps have 100 lm/W, HID lamps have 90 lm/W and LEDs have 140 lm/W. (These values are from commercial products by September 2012.)

Now a day’s replacement of standard incandescent lamps with LED lamps is the main point of the discussions. Today commercial LEDs have 10 times efficiency than the incandescent lamp but ten times expensive than incandescent lamps. Today it is the day like Edison's s bulb creation time, because both manufacturers try to decrease the cost of LED, LED bulbs and scientist try to fathom out the problems of LEDs.

Second issue for energy saving is power converters, which supplies appropriate energy source for the light sources. Traditional light sources, incandescent lamps do not use AC/DC power supplies. They are just resistors and no need for a power conversion from AC line. This feature makes incandescent lamp in with easiness of labor and application. Light sources like fluorescent lamps, HID lamps, work with original power converters (also called ballasts). Ballasts convert AC source to correct energy level for lamp. LEDs need essential power supplies for proper operation.

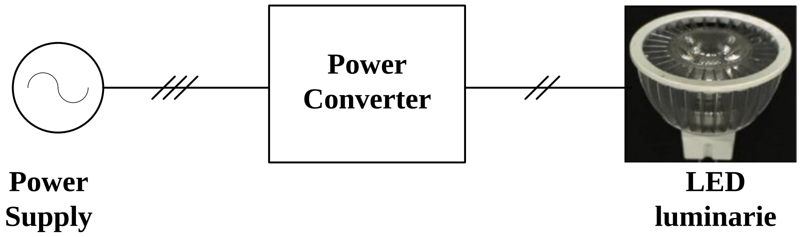

Figure 1.1 LED drive basic schematic

Organizations like Energy Star, EPA, IEC offer several restrictions and rules for manufacturers, in order to modify these converters. There are two phases for qualifications. First phase is to reduce the power consumption of devices in stand-by mode (off-mode). Second phase is to improving the active mode efficiency of devices. Designers effort to improve the power supply design, to provide qualified products.

Among these restrictions IEC 61000-3-2 standard stands for power supplies and restricts the power supplies in order to have specialties of power factor (PF) and harmonic limits. Manufacturers have to acquire these restrictions, during applying the foregoing rules of standby efficiency, active mode efficiency rules. These improvements on power supplies will boost the power quality of consumed energy.

Another main topic is to use the electric power with improved power quality. Previous issue of PF or harmonic limitation does not affect the efficiency or use of power converters. It shows that how the device uses the electrical energy. Usage of electrical energy affects a lot of materials inside the electric grid. High quality devices will not harm the grid components and will reduce the cost of the distribution system costs.

Power factor correction (PFC) is the combination of different circuits with conventional power converter in order to improve the power quality of the devices and try to maintain unity power factor. PFC circuits differentiate as passive and active; passive circuits use passive elements before the DC/DC stage of the SMPS and active PFC uses an active device to control PFC circuit. There are several topologies found out to solve this problem.

LED applications will increase exponentially in next ten years. It is true that the technology is a breakthrough in lighting and LEDs will save a lot of energy. It is necessary to consider LEDs not just as an effective electronic device; it has to be designed within a system. This system includes; designing thermal effects, LEDs operation and power supplies. These system parameters define the usability, efficiency and life-time of LED. Unfortunately, any wrong design; converts this superior technology to a big waste of money, waste of labor, and loss. In this system, power supplies have a key role; defining the working mechanism, power and life-time of the system. Even if, LEDs have 50.000 hours of operation if the power supply burns out after 5.000 hours, the system will be a trash.

LED applications are mainly in the range of 0 – 100 Watts. 0-20 Watt is for low-power applications 20-50W is for mid power and over 50 Watts is for high-power applications. Popular applications are low and mid-power because the traditional lamps already consume energy in this amount, so LEDs have to absorb low power. Even the long-life issue is not an excuse for preference.

There are different regulations for LEDs power supplies; similar to other light engines. However, LEDs power supply has to be low cost and small size. Also, LED power supplies have to be high power quality devices. In these limitations, most appropriate power supplies for LEDs are the **single stage PFC power supplies**.

1.2 Single-Stage PFC Power Supply

Single-stage PFC power supply is the integrated version of two stage PFC switch mode power supplies (SMPS). SMPSs are the improved versions of traditional power supplies. These power converters have an AC/DC rectifier and a DC/DC stage to produce output due to end user needs. "Switch mode" comes from switching elements of DC/DC stage of the converter. Basic working principle is switching the input voltage and transferring energy to the output stage by this action.

Conventional devices do not meet the requirements for power quality. Because of this, designers use another stage, power factor correction (PFC stage) to improve power quality. Designers integrate this extra stage to converters and get two stage PFC power supplies. These devices can achieve unity power factor. There are various types and topologies of PFC stages, like fundamental converters or input current shaper cells. However, there are some drawbacks of two stage power supply. First method of two stage power converter is active PFC; which has an extra active control device different from the active device of SMPS stage. These two switching components introduce design problems and high loss. Second method is passive PFC, which is a bulky design with a large area of converter. Another fact is; lot of components will introduce a lot of expense and design problems. Researchers introduced a new design with the developed version of two-stage power converters; as single-stage PFC power supplies (SSPS).

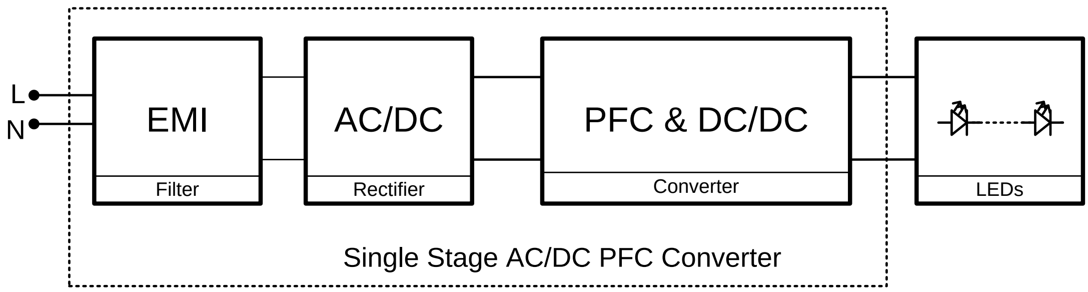

Figure 1.2 Basic schematic of single-stage PFC power converter for LED drive

SSPS combine the two stages of PFC and DC/DC stage in to one stage with one active control device provides both properties in one stage. These converters use several topologies of developed AC/DC converters; also establish a new form from two-stage PFC power supplies detailed in chapter3. SSPS have simpler control and fewer components with respect to two stage power converters. In addition to simpler control, these designs are cost-effective. SSPSs are excellent designs for the applications having power lower than 200W.

LEDs and SSPS are the perfect solution for new age lighting system. LEDs need power supplies that have low-cost, small-size and proper for standards. Most of the LED applications are low and mid power which, are lower than 50 Watts. The high power applications are highest 150 Watts. Therefore, SSPSs are perfect solutions for LED applications.

1.3 Scope of Thesis

The motivation point of this thesis is to the research of LEDs, power supplies and investigating single-stage PFC power supplies. The scope of this thesis is the single stage power converters for LED applications. This research involves theoretical calculations, simulations and experimental studies of selected converters. Solid state Lighting is a developing market and power supplies for LEDs are developing with LEDs. Already manufacturers begin to produce power supplies, with high PFC values and low harmonics better than the standards. The reason is the standards are subject to change in few years, and there will be more obligations in the future.

Chapter two covers LEDs in detail. First part is the definition of LEDs and basic characteristics of LEDs working principle and structure. Next part is the state-of-art for LEDs; the advantages, disadvantages and differences with respect to other light sources. The light sources and light are not the issue of this thesis; but it is the result of the application. So light is introduced to give an intense understanding. Next part is the LEDs electrical characteristic and model. Final part is the LED drive requirements and standards.
Chapter 3 involves the power supplies for LEDs. The first section covers power supply types and developments. Next section is the basic stages of power supplies, power issues and power factor correction. Next section covers DC drive stages, DC-DC converters and

different topologies of DC-DC converters. In this section, examples illustrate the use of basic converters for LEDs. Next part is the high power quality converters which are two-stage PFC power supplies. Also this part includes different applications and some advantage and disadvantages of two stage converters. Next section is the pivot point of this thesis which is the single stage PFC power supplies. This part covers the different topologies of single stage power converters from the first arrangements in 1990s until the developed converters used in the market. Final section introduces three distinctive types of single stage converters for LED applications; which are selected special purposes.

In next three chapters, chapter four, five and six; are the detailed analysis of these three SSPS. First section is the introduction of the converter topology. Next section covers DC analysis of DC-DC stage and the working mechanism of proposed topology. Next section includes design of converter; first detailing the specifications of the converter and then defining the circuit components. This section also covers unique controllers in detail with their internal operation mechanism and their remarkable properties. Next stage is the computer simulations of converters, with detailing operation mechanism and analyzing the performance. Final part is the implementation of hardware, printed circuit board design and experimental testing.

Chapter seven complete the three SSPS by comparing the performances, unit counts and price. This section involves the advantages and disadvantages with respect to each other.
This thesis studies single stage PFC power supplies for LEDs, with various applications, converters and their performances. LED technology is the new area of lighting market and developments show the high demand of this component. The main focus point is single-stage PFC power supplies for LED applications, a developed power electronic device for a developing lighting industry

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CHAPTER 2

NEW LIGHT SOURCE: LEDS

2.1 Introduction

LEDs rose from being a basic signal component to an efficient light source. It introduced better performance, long life-time and better effects in some applications. Researchers established the principle of light emitting 100 years ago, but use of LED as a light source has a history of just 10 years. Unfortunately, researchers forgot this technological device for a long time. The performance, developments and growth in the applications show that it is the light of the new century [1]. LEDs have one percent of usage with in the light sources, but each year its use increases exponentially. Resources show that LED has a market of US$ 7 billion in 2009 and grow up to US$10.7 billion in 2010 [1].

In fact of the advantages of LEDs, there are still a lot of work should be performed. LEDs life-time prediction, thermal sensitivity, color stability; voltage change is still subjects for researchers. This chapter introduces the LEDs with its definition, the operation of light emitting and historic development. Next section is LED semiconductor structure and the electrical properties. Another key thing is the state-of-art of LEDs, the innovation of LEDs with respect to other light sources. In order to understand LEDs, designer has to understand the characterization and the definition of light which introduced in other sections. After defining the model of LEDs and the drive requirements of LEDs, final section covers the standards and requirements of AC-DC LED drivers.

2.2 LEDs; Definition and Development

Currently, scientific institutions focus on establishing the definitions of solid state lighting devices for a common understanding of terminology. Illuminating Engineering Society defined LED as "*Light Emitting Diode (LED) is a p-n junction semiconductor device that emits incoherent optical radiation when forward biased. The optical emission may be in the ultraviolet, visible, or infrared wavelength."*[2]

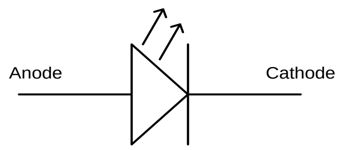


Figure 2.1 Electronic model of LED

The light output mechanism of LEDs is called *injection luminescence*, which refers that light emission is due to radiative recombination of excess electrons and holes; these produced by current injection with small energy losses. Light emission from a solid state material is caused by an electrical power source termed as *electroluminescence* [3]. Electroluminescence is emission in excess of blackbody radiation that is excited by an electrical field, occurs in a variety of systems under different conditions [4].

Henry J. Round, a radio engineer from Marconi Labs, reported this phenomenon of electroluminescence in 1907. Round produced light by touching the SiC crystal with electrodes, and formed first light emitting-diode. In 1928, Lossev reported the investigations of luminescence with silicon-carbide (SiC) metal. However, researchers could not explain physical basis of LEDs at that time. In 1955, *Braunstein* observed infrared emission from Gallium Arsenide (GaAs), gallium antimonide (GaSb), indium phosphide (InP) and silicon-germanium (SiGe). [5]

Nick Holonyak invented the first practical visible-spectrum (red) LED in 1962. In 1972, a former student of Holonyak improved brightness of red LED by a factor of ten. In 1976, T.P. Pearsall created first high-brightness, high efficiency LEDs for optical telecommunications.

The revolution of P-LEDs begin by the invention of high brightness blue (Gallium nitride) LED by Shuji Nakamura in 1991 which is awarded with Millennium Technology Prize in 2006. Also at the same time Cree Company introduced blue LED based on Silicon Carbide (SiC).

The figure 2.2 shows the evolution of LEDs compared to conventional light sources. As in the figure Thomas Edison’s first bulb was 1.4 lumens per watts (lm/W) and improved to 14 lm/W. Developments show that LEDs performance run out as compared to incandescent lamps. Also, the structure of SiC was a breakthrough to produce high-brightness blue LED which led the process of producing power LEDs. Figure also shows other light sources and different structured LEDs.

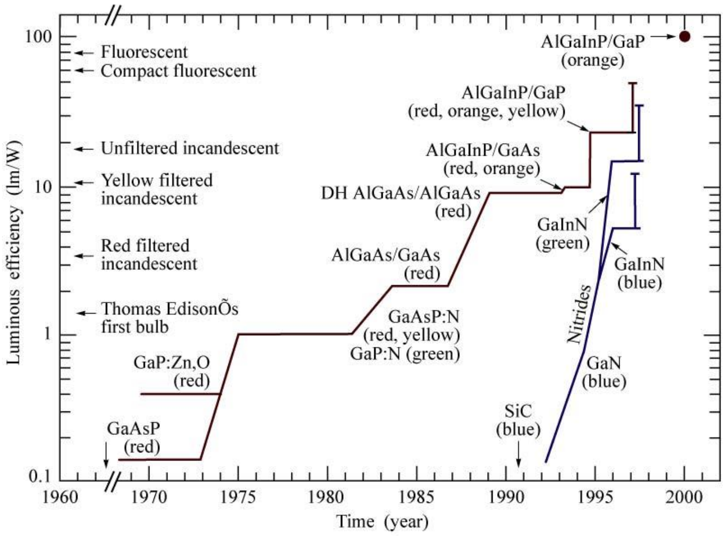


Figure 2.2 Development of LEDs within 40 years (Schubert 2003, Pg 168)

Next figure introduces Haitz Law which states that every 10 year LEDs price will decrease with an amount of 1/10 and the lumen performance will increase with an amount of x20. A 60 Watt incandescent lamp has 1000 lumens with 17 lm/watt and cost of 1 $. Purple line shows the lumen performance of LED and blue line shows the price of LEDs.

As figure shows, the brightness levels of LEDs were extremely low. Major development in LEDs is the luminous efficiency which doubled in every four years [3,167-169]. Figure 2.3

shows the evolution of visible LEDs. It starts from 1960s which first LED having 0.1lm/watt and increased up to 40 lm/watt in 30 years. Another significant point was, use of Silicon material as a LED substrate in 1990s; coming with a theory of devices with integrated Si double its performance in each 18 months.

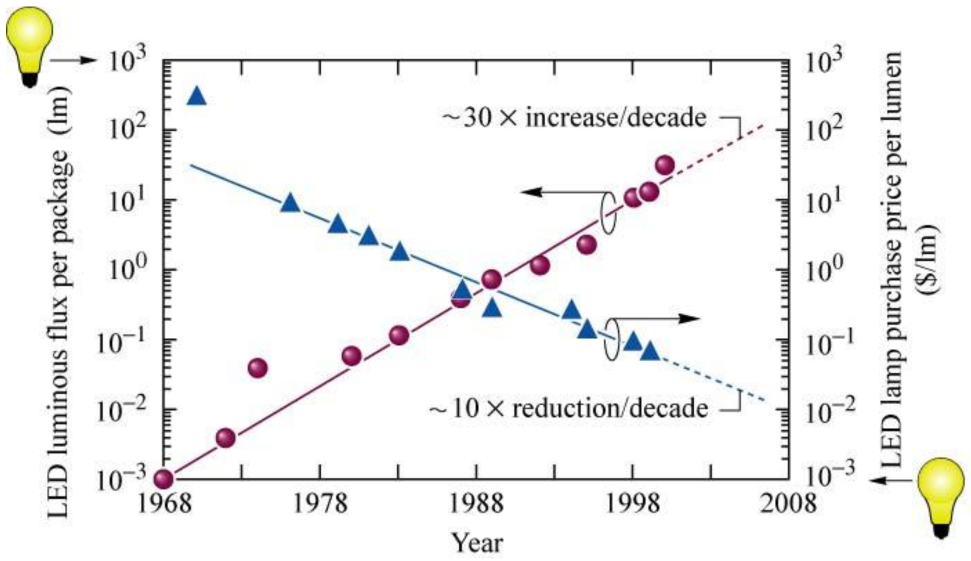


Figure 2.3 LED performance and cost change in 40 years (Schubert 2003 Pg 170)

High prices of production restrict the use of LEDs. After initiation of individual chip fabrications and innovative methods of packing made LED production cheaper. After these developments LEDs became indicator lamps and replaced incandescent and neon indicators. All electronic devices, TVs, radios, telephones, calculators and watches have these indicators. Next applications of LEDs are the one-dimensional graph display and image projection systems. The development of liquid-crystals limits the use of LEDs in this area. The development of different colors of LEDs make them popular again and by 1980s first transparent-substrate AlGaAs LEDs introduced as high brightness electroluminescence device. Increase in brightness LEDs removed to a new area of all applications of artificial lighting with PLEDs.

Manufacturers named PLEDs as XLamp from Cree, Lumileds from Philips, and Dragon from Osram. They are used in 350 mA with a power of 1 Watts. *Cree Inc* introduced 150 lm/W LEDs with compatible prices in July 2012 and introduced a record 254 lm/W White LED in laboratory conditions. Osram and Philips also introduce high efficiency PLEDs.

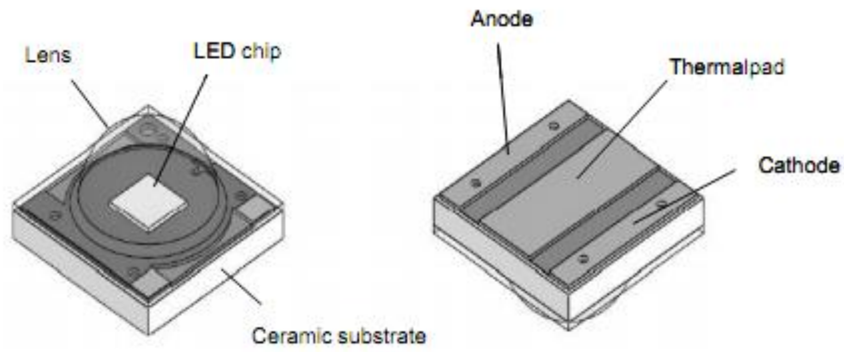


Figure 2.4 Structure of LED from Cree, Xlamp XP-G LED [6]

Each LED type developed after invention of advanced technology materials and manufacturing techniques. LEDs can be used in high power; however the effectiveness dropped to critical levels as power increased. LEDs are small, reliable, bright and effective from the other light sources. It can be produced in different colors and also in varying color temperatures. LEDs have electrical and thermal parameters that affect the life-time of the LEDs.

2.3 LEDs Structure and Electrical Characteristics

There are different types of LEDs that have different structures. Common principle is the semiconductor electroluminescent structure that comprises a radiative recombination. Electron-hole recombination mechanism converts energy of an electron into optical energy. When the condition occurs in ideal conditions, LED emits one photon for every injected electron. So there is optical efficiency of LEDs semiconductor structure, which causes every photon created, cannot leave the LEDs semiconductor space.

The photon energy is approximately equal to the band gap energy (E_g). The conversation of energy from electrical to optical requires a **drive voltage** or **forward voltage (V)** of LED is equal to the band gap energy. The following equation is derived from energy conservation;

$$V = \frac{hv}{e} \approx \frac{E_g}{e} \tag{2.1}$$

There are mechanisms that cause the drive voltage to be different from the above value. Diode could have series resistance causing voltage loss or energy loss due holes. These mechanisms change the forward voltage equation of a LED. On the other hand, forward voltage has temperature dependence, which we will discuss the effects in later chapters. The equation 2.2 shows the I-V characteristic of an ideal LED.

$$I = I_s\,(e^{\frac{eV-Eg}{kT}} - 1) \qquad (2.2)$$

In the equation; I is forward current of LED,   Is is saturation current of LED, V is forward voltage drop of LED, k is Boltzmann constant, T is temperature, e is electron voltage.
Diode forward voltage is temperature dependent even if the drive current of LED is constant. Voltage drop across the diode will change. Solving the equation 2.2 brings the forward voltage as a function of temperature.

In the equation 2.3 right side is the change of energy level with respect to temperature, in which as temperature increases, energy gap of semiconductors decreases. The reason of the LED voltage change is; the recombination process become easier and voltage drop decreases 2mV for each degree as the temperature rises [5].

$$V\ \ T\ = \frac{kT}{e} * \ \ln\frac{I}{I_s}\ + \ \frac{E_g\ \ T}{e} \qquad (2.3)$$

The forward voltage is also dependent on the junction temperature of LED. The following figure 2.5 shows the normalized forward voltage changing with respect to temperature. Model of standard diodes is a voltage source and a series resistor. LED behavior is similar to the constant voltage loads with equivalent series resistor (ESR). The forward voltage depends on the type of LED. This type is both the semiconductor structure and the color of LED. Another issue is the same color and structured LEDs can have a variation of voltage drop because of the production. During the production of LEDs, there are variations with respect to tolerance of wavelength about 10%. I-V characteristics for low power LEDs shown in figure 2.5.

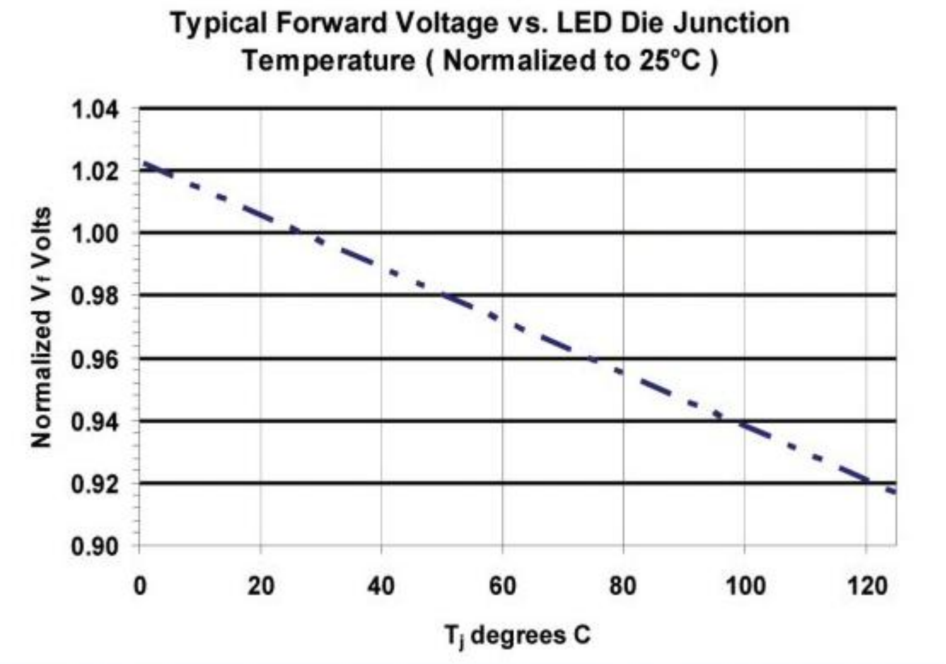


Figure 2.5 Forward voltage change with respect to junction temperature of LED

LEDs have different forward voltages; even if LED color and LED semiconductor structure is same. It is extremely difficult to determine the same forward voltage LEDs, so the manufacturers define another variable in order to select the different LEDs in voltage and color bins. The typical white, blue and green LEDs have typical forward voltage in the range of 3 Volts to 4V, amber and red LEDs have 2 to 2.5V. Manufacturers provide the forward voltage value of LEDs at 350 mA as an industrial standard. LEDs forward voltages also dependent on their package, in which bigger packages have lower forward voltages.

For example, a LED XLamp XP-G from Cree have rated current of 1.5 A, and have 3 V of forward voltage drop when operated at 350 mA. Another LED XP-C from Cree has rated current of 500 mA; when operated at 350 mA it has a forward voltage drop of 3.5 V. This example shows that even in the same package, different types of LEDs have different forward voltage and also different powers.

Figure 2.6 shows I-V characteristics of different LEDs. The manufacturers list labels to the product, and they define the voltage range of a LED as bin.

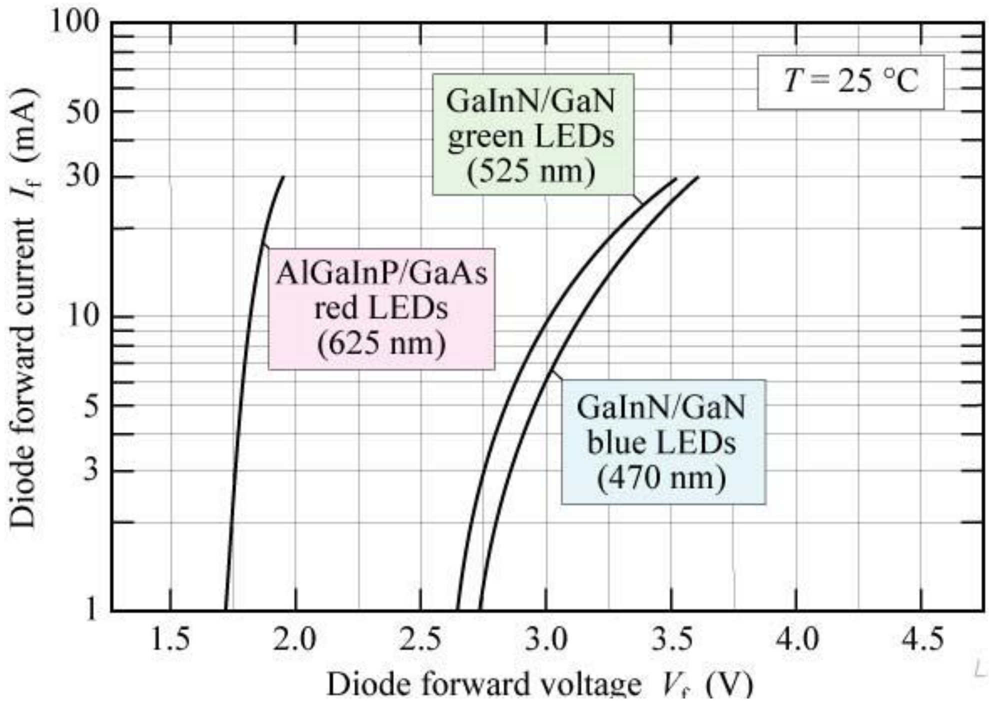


Figure 2.6 I-V characteristics of LEDs (Schubert 2012, pg173)

An example of binning of General Electric's LED *Vio 4 Watt* is in Table 2.1.

Table 2.1 Forward voltage bins of *General Electric's* LED *Vio*

Bin number	**Voltage Min.**	**Voltage Max**
0	3	3.25
1	3.25	3.5
2	3.5	3.75
3	3.75	4

Reverse breakdown is a general concern for diodes. All diodes including LEDs operate when there is positive voltage from anode to cathode. The current flow starts when the applied voltage exceeds the threshold voltage. The threshold voltage for *Silicon* diode is 0.7 V, *Schottky* diode 0.3 V, *Germanium* diode 0.2 V, and for LEDs 1.2 V. If there is enough voltage across cathode to anode, diodes conduct in the opposite direction to forward current which is the *reverse breakdown voltage*. There are diodes like *Zener* and *Avalanche* whose are suitable for this operation mode. On the other hand, for standard diodes this is an intolerable situation. The rectifier diodes could be produced with high breakdown voltages which is 200 V to 1000 V, even if there is a mistake in the circuit or just wrong application of having negative input from the power supply, the diodes resist to this voltage. Unfortunately, this is different for the LEDs whose have 5V of breakdown voltage. Even if, the connection of LEDs are in series, the total breakdown voltage will be lower from the supply. This condition cause several failures but have two solutions. First a series rectifier diode can be used, and even if there is a high reverse voltage, there can be breakdown voltage of minimum 200 V. At this point, only disadvantage is rectifier diode operates continually and dissipates power as LEDs operate. Second solution is using an anti- parallel diode with the LEDs and prevents the negative voltage by conducting at that condition.

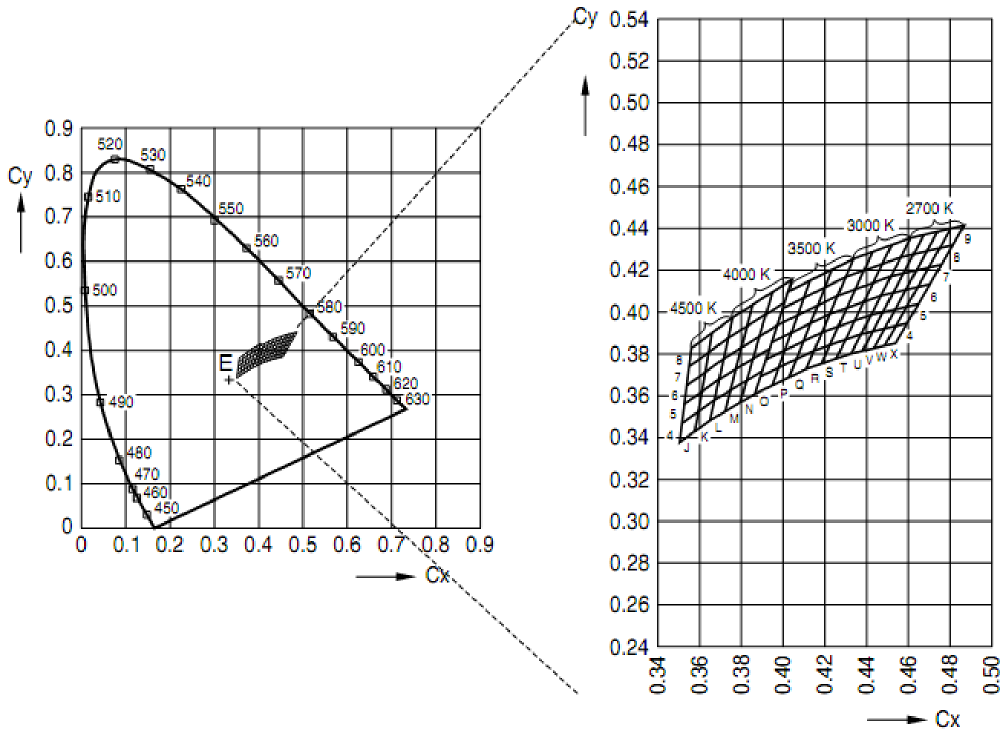


Figure 2.7 LEDs chromaticity groups from *Osram Ostar* [7]

One of the challenges is to manufacture white LEDs because white light is not just from one wavelength. White light sources including sun emits light in the full spectrum of colors and white light are the combination of these colors. In order to produce white LEDs there are two methods; one of them is mixing red-green-blue in some ratio and the other one is applying phosphor substrate over blue LED. The usual method is using phosphor based LEDs. These products differentiate with respect to color temperatures in white light starting from 2700 K-3000 K called as warm white 3000K-4000K called as daylight and 4500 K - 10000 K cool white. This technology stills continue to develop and try to solve efficiency and droop problems.

2.4 State of Art of LEDs

The developments and future goals show that LED is a perfect solution for lighting applications and an energy efficient material that will save a lot of energy. Just with a simple calculation, today there are about 20 billion lamps in the world. If we make a basic assessment of changing every traditional lamp with proper LED lamps with 50% energy saving. Everyday 300 billion Wh is saved. Next section is the advantages, disadvantages of LEDs and comparison of LEDs with other light sources.

2.4.1 Advantages

This is a fact that the main point, and advantage of LEDs is the life-time. Its life-time is about 50.000; which is 50 times of incandescent lamps, and five times of fluorescent lamps life-time. Life-time depends on the internal chip temperature of LED. In perfect conditions, they can go up to 100.000 hours of operation. The life-time of LEDs is not the end of LED; its lumen output start to decrease standard of LM70, this test indicates the time when LED’s lumen output come to a value of 70% of its beginning lumen output. For other lamps, cycling is another matter for life-time problem. For example, fluorescent lamps have limited cycle times. Profitably LED does not have a limitation for cycling. In addition, LEDs on/off time is remarkably fast with respect to other sources. It takes nanoseconds to a LED to light on and light off. This feature allows LEDs even to be used in communication. This time is milliseconds for fluorescent light sources and several minutes for metal-halide and vapor based lamps. Also, consistent light output and consistent color settle in several minutes in these lamps.

LEDs have a remarkably small size; the HBLEDs are about 5mm and PLEDs are surface-mounted devices in 3mm to 3mm packages. These devices have to be used with printed circuit boards and with heat sink. Low power devices do not need heat sinks, which make them straightforward to use in a lot of places. Also, a new lighting term redefined after this product; concealed lighting. They can be produced in various types of colors and with multi-colors on single LED. Hence forth the designer can obtain 16 million colors from LEDs. Traditional light sources use color filters or significant painted lamps in order to obtain colors. Color film is an extra-cost and has limited application area. This feature makes LEDs popular in architectural lighting and with growth in digital electronics; infinity number of applications are on.

Another unique property is; the light output of LEDs can be directed from the source with the use of lenses. Other light sources give out light within 360° and reflectors used to guide the light output and increase the Lux of the light source. LEDs can be produced with a lens on it and manufacturers can specify the output angle of LED. Also, individual types of lenses used to direct and spread the light output of LEDs.

LEDs can be dimmed easily, without degrading its performance and changing its color. LED is an electronic component and its semiconductor structure provide various types of applications for dimming.

Light sources convert the electrical energy to light with an efficiency value. The lost energy is dissipated as heat. The incandescent lamps convert just 2% of the electrical energy to light, and the rest of energy is dissipated as heat directly to the air. Distinctly LEDs convert the electrical energy in a percentage of 30% and 70% to heat. Radiation is the transfer system of heat by using heat-sink. So LED luminary does not radiate heat into the medium. Incandescent lamps, metal halides cause the ambient hotter, which is a problem for markets, stores and public areas.

LEDs are resistant to shock voltages with appropriate electronic drive circuit. Any change or ripple in line voltage directly affects these lamps; which we are familiar with the decrease of the light output of incandescent lamps when washing machine starts to work. LEDs do not contain hazardous material like mercury in fluorescent lamps. Mercury is a harmful material which is both a manufacturing problem and usage problem. Fluorescent and metal halide lamps use mercury as the primary light source, because it emits light with 5 times more efficient than incandescent lamps and have 10 times life-time. A broken fluorescent lamp is harmful, and there should be a plastic bag to throw out the lamp without touching the material. The health effect of mercury is not proved, but allergic skin may react, and absorbed vapor of mercury by skin results as toxicity.

Fluorescent lamps flickers when they work for long time. LED does not have a problem of flickering because the LED drivers operate in high frequencies and this cannot be observed by the human eye.
LEDs can be used in harsh environments of low temperature. In addition in low temperatures the efficiency of the LEDs increases. By contrast, the other light sources like fluorescent do not work in low temperature.

2.4.2 Disadvantages

LEDs have high initial costs in these days. The predictions and developments show that initial costs will decrease by 1/10 within next 10 years. LEDs are temperature dependent devices. If there is an incorrect use of LEDs, the lifetime will decrease in large amounts. Correct driver for LEDs and respectful working conditions solve the temperature dependency problem of LEDs.

The incandescent lamps have a perfect value of Color Rendering Index (CRI) as 100%, which means the objects under these lamps can be identified perfectly by the human eye. This property cannot be acquired by fluorescents. LEDs developed high CRI values of 90%.

Nowadays researchers work on the health effect of blue light because the wavelength of cool white LED includes blue light in the limit of eye safety conditions. Blue light affects human health and results in sleep disorders.

Another problem of LEDs is droop issue of LEDs. Researchers call this issue as *dark secret* of LEDs [8]. It is the drop of the efficiency of light output of LEDs when current of LEDs increase. By this time no-one can answer the problem of droop and several people and companies are working to define this problem, its effects and results. Here, the recommended solution for designers is not using the LEDs in high currents even it is capable of these currents.

2.4.3 Comparison

Table 2.2 compares the light sources; with respect to efficacy and efficiency values. Efficacy is the variable showing the efficiency of converting electrical power to light. Unit of efficacy is lumen/watt. [9] The variables in table 2.2 are the products commercially available. The highest light source is pure green light which is 683 lumens. Here, the competition is to produce the light source more efficient inside the comparable price limits. Today LEDs have efficacy and efficiency values like fluorescent lamps, which double in next ten years.

Table 2.2 Light source comparison table

Light Source Category	**Light Source Type**	**Luminous efficacy (lm/W)**	**Luminous Efficiency**
Combustion	Candle	1	0.15%
Incandescent	Edison’s Lamp	1.4	0.2%
Incandescent	100 Watt Tungsten	14	2%
Fluorescent	32 Watt Compact Fluorescent	75	11%
Fluorescent	T8 with ballast @ 150 kHz	100	15%
Gas Discharge	Metal Halide	115	17%
Gas Discharge	Low Pressure Sodium	150	22%
LED	White LED	150	22%
LED	7 Watt (LED lamp)	60	8%
Ideal Source	Green Light at 555 nm	683	100%

The new electronic devices and new technology introduce new challenges of implementation. LEDs have challenges of implementation and production. PLEDs have heat transfer problems and the binning problem. Manufacturer of LEDs try to decrease the range of PLEDs in the same color, and luminary manufacturers are trying to adopt the LEDs in mass production. Next section is about light definition, in order to give a better understanding.

2.5 Light Definition and Terms

The definition of *"light"* has changed continually in history and still a subject that cannot be defined clearly. We know that light is an electromagnetic wave which carries light packages called photons. Physical properties of electromagnetic radiation can be defined by ***radiometric*** units. ***Photometric*** units characterize the light for human sensation.

Luminous intensity is the optical power of a light source and has units of ***candela*** (cd). The name comes from real candelas light intensity; one candela emits a luminous intensity of 1.0 cd. Luminous flux is light power of a source perceived by eye, and the unit as ***lumen*** (lm) also defined as*: "a monochromatic light source emitting power of (1/683) Watt at 555nm has a luminous flux of 1 lumen."* 1 candela equals 1 lumen per steradian: cd=lm/sr. Illuminance is luminous flux per unit area, and the unit is ***lux*** (lm/m^2) [2, pg220]. Lux can be measured by specific measurement devices. For example, full moon has 1 lux, direct sunlight has 100000 lux, and standard office lights are 400 lux. [10]

Another subject of differentiating light sources is colorimetry. Colorimetry includes color temperature, color rendering, chromaticity coordinates. Light sources cause different radiative distribution of red, green and blue cones having different luminous flux functions. Since this is a subjective quantity and cannot be measured, CIE standardized the measurement of color using ***color matching functions*** (figure 2.8) and ***chromaticity diagram***.

The degree of colors are X-Y-Z, tri-stimulus values (integrated among the wavelengths), from this values chromaticity coordinates "x, y, z" are calculated. And the light source can be placed into the chromaticity diagram shown in figure 2.9.

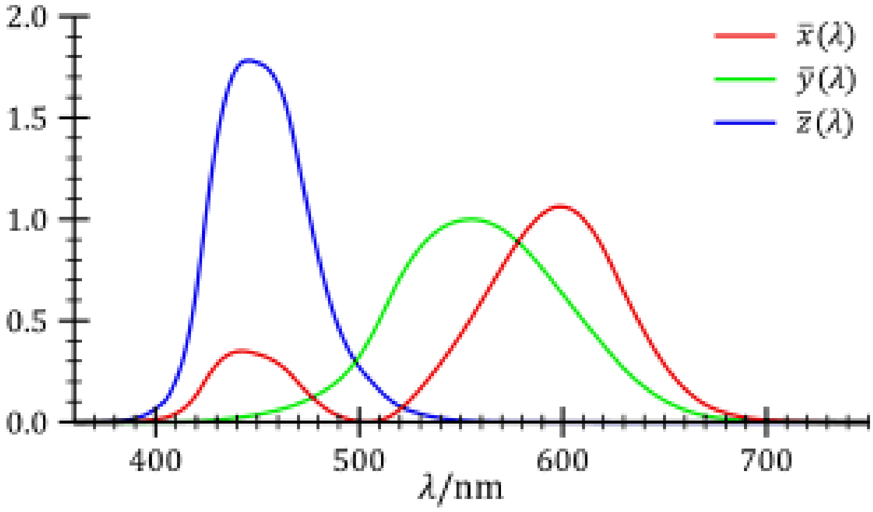


Figure 2.8 RGB color matching functions of LED

The chromaticity value z can be obtained from x and y coordinates, so it is not used on the diagram. By the help of chromaticity diagram, the definition of the colors of light sources can be given exactly. Uniform chromaticity diagrams with two variables stands for better understanding.

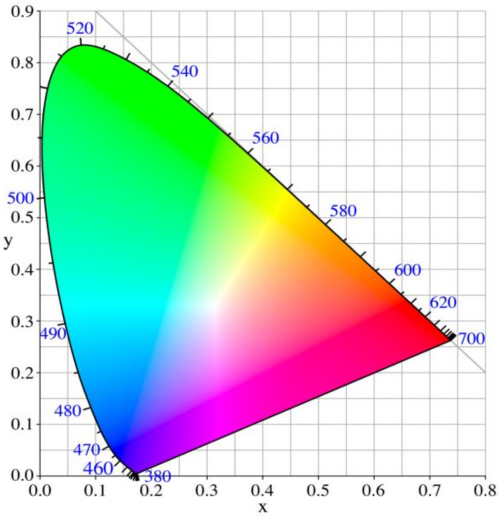


Figure 2.9 CIE chromaticity diagram

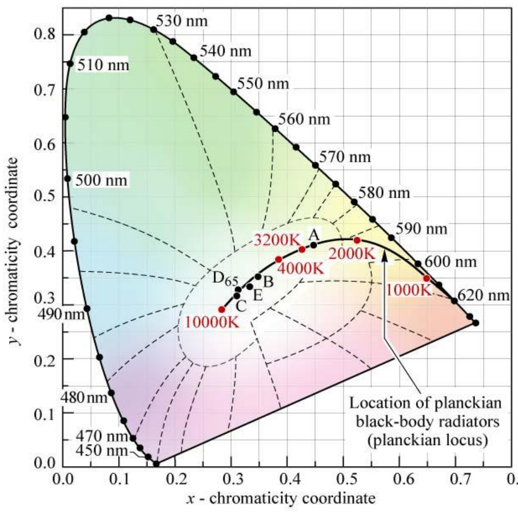


Figure 2.10 CIE chromaticity diagram inserted planckian function [4]

Another variable that used to define the white light source is ***color temperature***. The units of color temperature are "Kelvin" and which is the temperature of the planckian blackbody radiator.

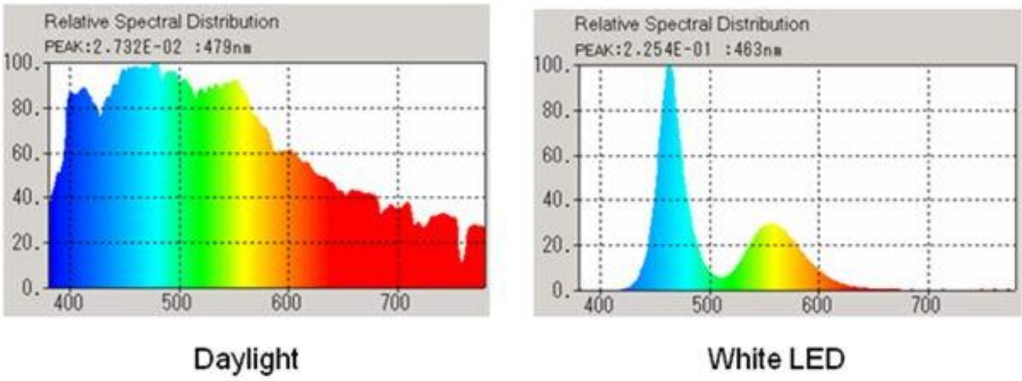


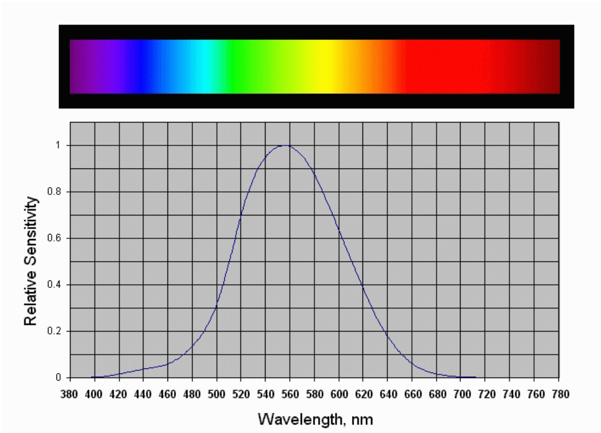
Figure 2.11 Spectral power distributions of daylight and white LED
http://www.pikeresearch.com/blog/articles/light-color-is-complicated

Figure 2.10 shows the planckian function, and the values changes from 1000K to 10000K. These color temperatures differentiate; over 4000K is cool white, 3000K-4000K is daylight, and lower than 3000K is warm white.

Sunlight has a spectral power distribution of colors. Also white LED can be introduced with in this manner. The following graph illustrates the different lamp sources with respect to daylight

An important quality of white light emitters and comparison variable is **color rendering index** (CRI). It is the quality of a light source, how it renders all of the colors of an illuminated object by that light source. Ideal light source has CRI = 100 and the incandescent sources have best CRI values. The LEDs also have high CRI about 80 with respect to other sources. We defined color rendering index for different light sources in appendix A.1.

Eye sensitivity function has the value of 1 at the green light, 555 nm. Radiometric light power can be converted to luminous flux (Φ_{lum}) by the following equation.



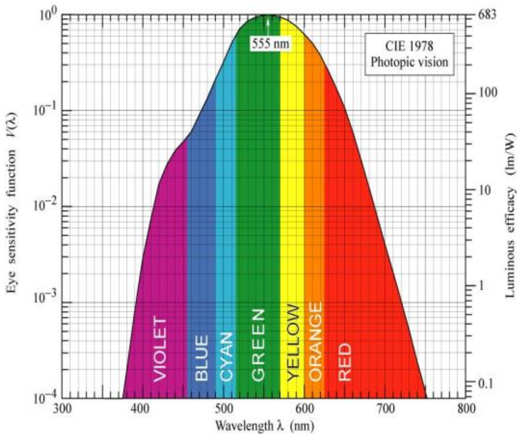


Figure 2.12 Relative sensitivity versus wavelength CIE1988

Figure 2.13 Eye sensitivity function versus wavelength CIE 1978

$$\Phi_{lum} = 683\frac{lm}{W} \quad V\ \lambda\ P\ \lambda\ d\lambda \tag{2.4}$$

Another fact is that the human eye sensitivity which changes with respect to different colors. For amber or orange colors, the human eye has the high sensitivity. Another note human eye is sensitive to green light which is 555nm. This issue shows that, green LEDs seems to be brighter to the human eye. There is a function for **eye sensitivity** V(λ). which used for the change of radiometric to photometric units. Figure 2.12 and figure 2.13 introduce this function.

Luminous efficacy measured in lumen/watt for optical power. This is the efficiency of changing optical power to luminous flux;

$$Luminous\ Efficacy = \frac{luminous\ flux}{optical\ power} = \frac{\Phi_{lum}}{P} \tag{2.5}$$

$$Optical\ Power = P = \quad P(\lambda)d\lambda \tag{2.6}$$

Luminous efficiency is the parameter used for comparing the light sources is luminous flux divided by input electrical power given in equation 2.7.

$$luminous\ efficiency = \frac{luminous\ flux}{electrical\ power} = \frac{\Phi_{lum}}{IV} \qquad (2.7)$$

2.6 LEDs Electrical and Thermal Model

2.6.1 LED Electrical Model

Driving LEDs with constant voltage sources is not recommended for various reasons. First of all LEDs are current dependent devices. Diodes are not linear devices like resistors namely the voltage and current are not proportional. So the Ohm’s Law does not apply to the diodes. Another issue is little change in forward voltage affect significant change in the current of LED. Without looking the equations, the figure 2.6, shows the strong effect of voltage. For 3.0 V, the current pass through LED is 350 mA, after 100 mV rise current goes up to 500 mA, after 250 mV rise current increase to 900 mA; further increase in forward voltage will damage the LEDs. In this manner if we have extra forward voltage variation it will be terribly hard to adjust the light output of the LED. The equations and the behavior of LEDs show that LEDs are current devices. Therefore, the source have to be current controlled, or constant current in order to guarantee the constant lumen output and same working principles for different type of LEDs.

The equivalent circuits are essential for electronic devices for better understanding. Figure 2.14 shows the equivalent circuit for LED which is a Zener diode and a resistor.

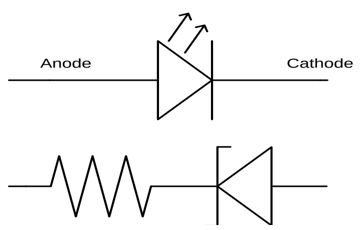


Figure 2.14 Equivalent model of LED

This model also can be used as a Dummy load, in order to avoiding the failures of expensive LEDs. ESR, equivalent series resistance, defined because semiconductors are not good conductors and there is another voltage drop on the series resistance. Each LED can have different ESR values with respect to production.

The ESR value can be obtained from the I-V characteristic graph; like shown in figure 2.15 XP-E HEW from Cree. Low power LEDs like high-brightness LEDs work with maximum 50 mA and have an ESR value of 20-25 ohms.

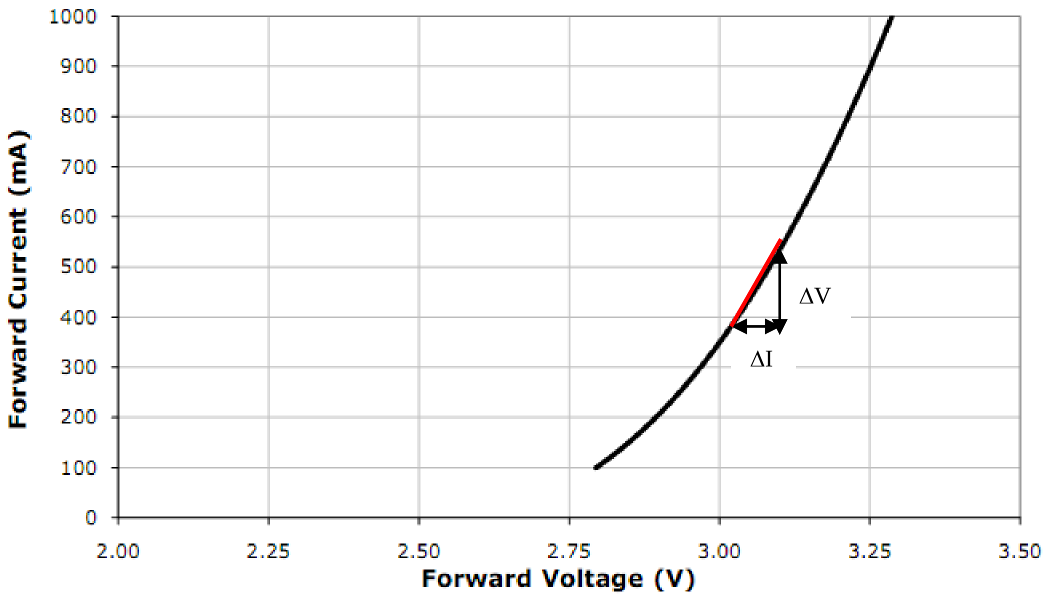


Figure 2.15 I-V characteristic of *Cree Xp-E* at 25°C [11]

Differently power LEDs ESR value is 1-2 ohms and the minimum current is about 350 mA so the voltage variation plays a crucial role. ESR value is not division of forward voltage to forward current it is a division of the “change” in voltage to “change” in current. ESR is the slope of the graph at the exact point of operation.

2.6.2 LED Thermal Model

This section includes thermal model and thermal management for LEDs. Thermal properties and operation temperature have a significant role on LEDs lumen output, LEDs electrical characteristics and LEDs life-time. In order to correct operation for LEDs, heat generated by LEDs has to be transferred easily from the LED package and the temperature at the junction point of LEDs has to be regulated. Correct operation or heat management covers, thermal design, LEDs assembly and operation mechanism. Unless LEDs can run up to high temperatures and efficiency drops and life-time drops to exceptionally low values; which will defeat all of the advantage of LEDs.

Table 2.3 Thermal parameters and units and analogous electrical parameters

Thermal Parameter	Parameter Symbol	Thermal Unit	Electrical Parameter	Parameter Symbol	Electrical Unit
Thermal Resistance	R_{th}	°C/W	Resistance	R	Ohm
Thermal Capacitance	C_{th}	J/W	Capacitance	C	Farad
Thermal Power	P_t	W	Current	A	Ampere
Temperature	T	°C	Voltage	V	Volt

Thermal properties are analogous to electrical parameters; resistance, capacitance, voltage and current. Thermal resistance is the materials ability to resist the heat flow through it. If the material has high thermal resistance, it transfers heat extremely slowly. Thermal resistance is similar to electrical resistance, as resistance increase the voltage drop on it increases. Thermal resistance has unit of Kelvin per Watts. Another thermal parameter is thermal capacity. It is the similar to capacitance; it is the ability of the material to store thermal energy. Analogously to a little water reaches boiling temperature quickly but bigger amount of water reaches boiling temperature slower; the difference between two situations is thermal capacitance [3]. Table 2.2 details thermal parameters and units with giving analogous variables of electrical characteristics.

The temperature drop on a material can be calculated with respect to these variables. Similarly to Ohms law (V=I*R) temperature is the product of thermal resistance and thermal power.

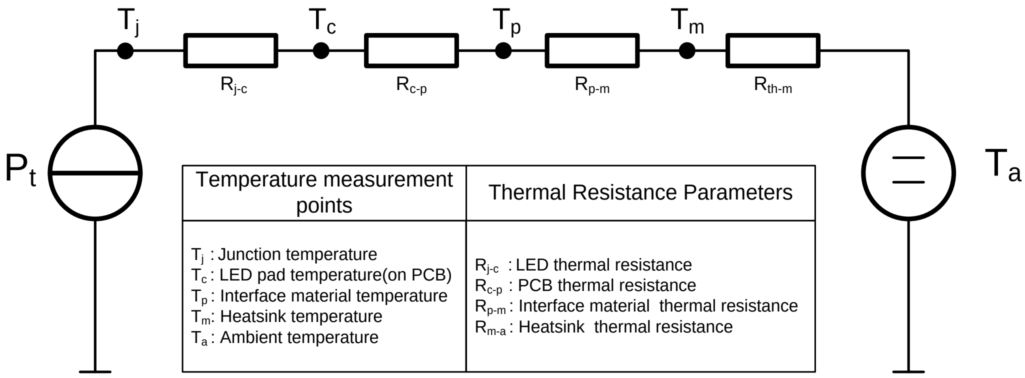


Figure 2.16 Thermal model of LED module

Thermal calculation is performed with the thermal model of the circuit element and used for various electronic components. Most of the electronic components dissipate power as heat and this heat should be transferred from the package. For heat transfer, thermal calculation has to be performed. Figure 2.16 introduces thermal model and thermal measurement points of LED.

Thermal model is used to calculate the temperature value at the junction point of LED or the expected thermal resistance value for the heat-sink. The temperature difference two points from ambient to LED junction point found out by calculating the total thermal resistance between two points by:

$$R_{th-tot} = R_{j-c} + R_{c-p} + R_{p-h} + R_{th-m} \quad : °C/W \tag{2.8}$$

LEDs dissipate the some part of power as heat and some as light. Equation 2.9 gives the power dissipation where LED forward voltage is V_{led}, forward current is i_{led} and power dissipation is P_t

$$P_t = V_{led} i_{led} \tag{2.9}$$

Temperature difference is calculated by multiplying the thermal power and total resistance value as shown in equation 2.10. In the equation variable are; LED thermal junction temperature (T_j), ambient temperature (T_a), total thermal resistance (R_{tot}).

$$\Delta T = T_j - T_a = P_t R_{th-tot} \tag{2.10}$$

The figure 2.17 shows LED engine; LEDs, printed circuit board (PCB), thermal interface material and heat sink.

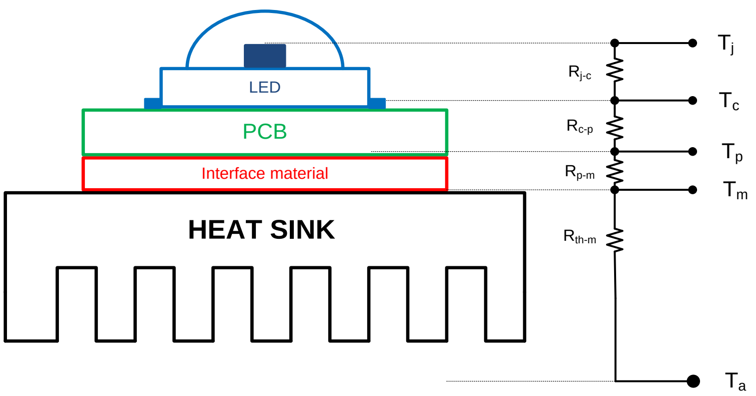


Figure 2.17 Thermal model of LED integrated system

As shown in the figure each of the part has its thermal resistance. Each part causes temperature drop. Manufacturers define thermal resistance values of these materials. LEDs have different values for different LEDs the thermal resistance for *Cree* XP-G2 LED is 6°C/W, *Philips Luxeon A* 6°C/W which are the most developed LEDs. (Previous versions have thermal resistance of 10°C/W.) PCB is the material that electronic components assembled.

There are various types of PCB materials; for LEDs most used material is metal-core PCB (MCPCB). MCPCB has different types changing with respect to their thermal conductivity values. Standard MCPCB's have thermal resistance of 4-5 °C/W; also there are high conductivity MCPCBs with 0.5-1 °C/W. Other types of PCB's used for LEDs are FR-4, FR-2 or CEM1 materials. These PCBs are low cost with respect to MCPCBs, but they have a high value of thermal resistance. These PCBs are for low power applications (LEDs with 0.2 Watts). They are only used for PLEDs with specific design and a power limitation. In order to choose the PCB type the application has to be detailed and with respect to total power and the area of the PCB.

Table 2.4 TIM comparison (Dow Corning, http://www.dowcorning.com/content/etronics/etronicswet/)

Property	Encapsulant	Adhesive	Phase Change	Compound	Gap Fill Pads	Adhesive Films
Bulk Conductivity	Excellent	Good	Excellent	Good	Excellent	Good
Thermal Resistance	Good	Good	Excellent	Excellent	Fair	Poor
Bond Line Thickness	Good	Excellent	Excellent	Excellent	Poor	Fair
Production Automation	Excellent	Excellent	Fair	Excellent	Fair	Fair
Re-workability	Good	Poor	Excellent	Good	Excellent	Poor
Stress Relief	Good	Fair	Good	Excellent	Good	Fair

Thermal interface material (TIM) is the general name of thermal conductive materials. TIM transfers heat from PCB to heat-sink. The reason to use this material is the surface of the heat-sink may not have a smooth surface. When PCBs are mounted to the heat-sink, there can be parts of PCB does not stamp on the heat-sink perfectly. TIMs remove this effect and provide perfect assembly. There are various materials used as TIM; adhesives, gels, compounds, films and pads. These materials change with respect to the properties; thermal resistance, thickness, production automation, rework ability. A supplier Dow Corning introduces a comparison table for these materials. Heat-sink is the material that transfers heat from the LED to ambient. Here, three methods of heat transfer occur; convection, conduction and radiation. Conduction and convection are the less effective transfer types; radiation is the main method to transfer heat. There are various products used for this aim, but best and most used material is aluminum and copper based materials. The thermal property of heat sink depends on the shape, the core of the material, type of the material and surface finish of the material.

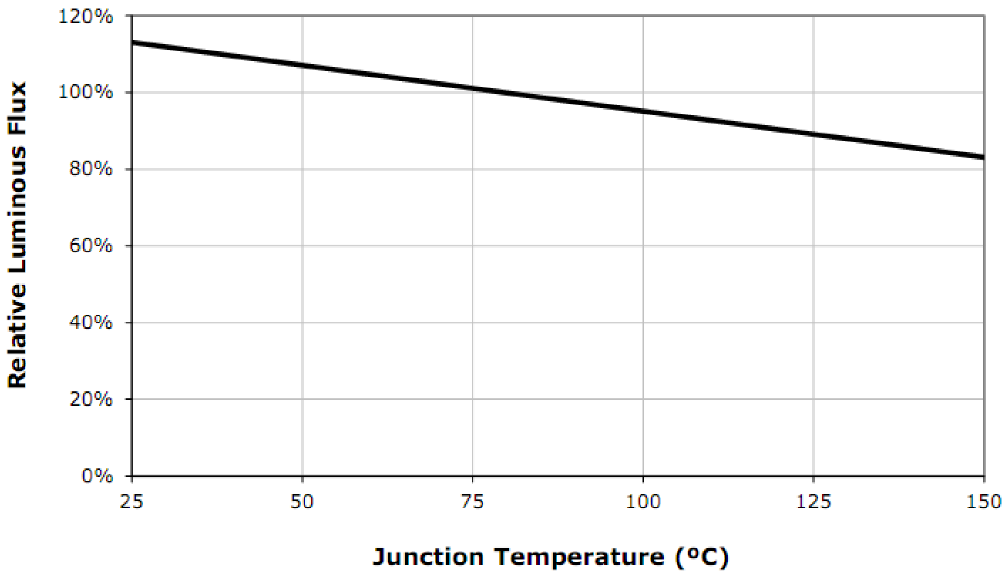


Figure 2.18 LED luminous flux change by junction temperature of LED [11]

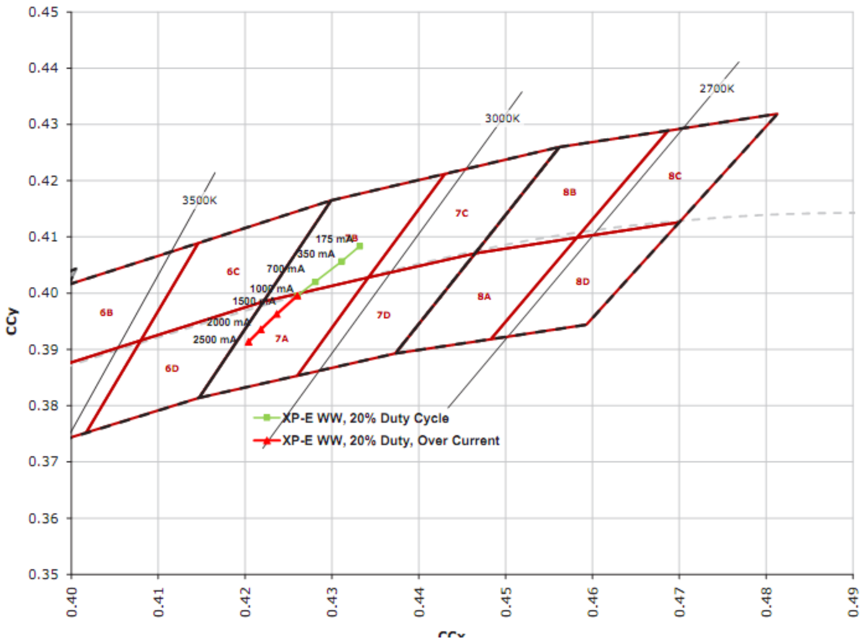


Figure 2.19 LED color change at different drive current values

2.7 LED Drive Requirements

The structure, load type and behavior of LEDs proofs that LEDs have to be driven by DC constant current in order to correct operation of color, constant lumen output, steady thermal conditions and long life-time.

LEDs color temperature value changes with respect to applied current. Figure 2.19 shows this effect. Current value changes from 175 mA to 2500 mA and the chromaticity value of LED changes with respect to changing current. Beside several drawbacks, LEDs color will change noticeably. LEDs lumen output is highly dependent on the current of LEDs. As shown in figure 2.20; change of 500 mA creates 100% lumen output difference. As we calculated in the previous part 500mA current difference can be formed just with increasing the applied voltage by 100 mV.

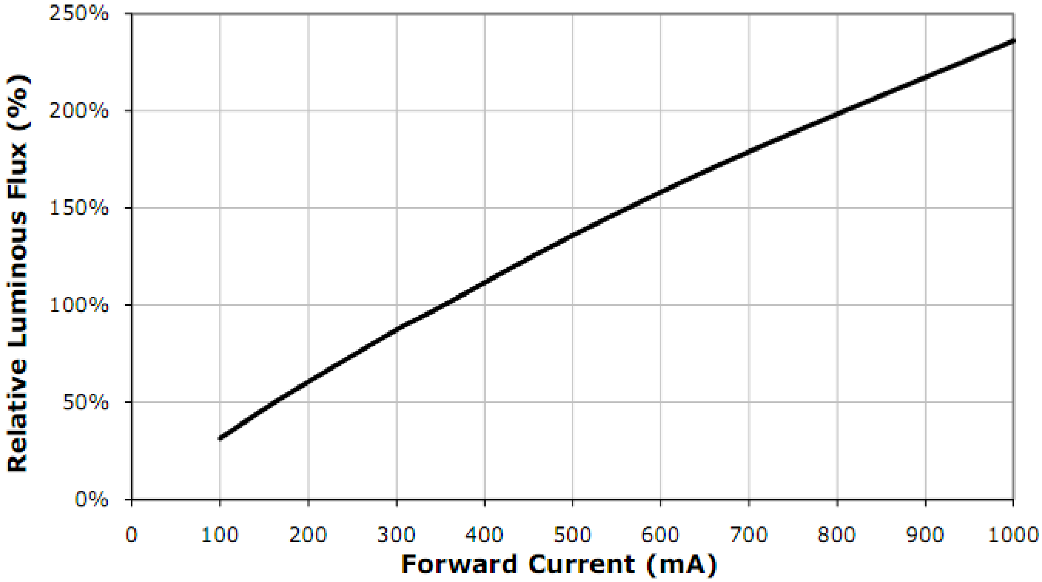


Figure 2.20 Luminous flux change with respect LED forward current, Cree Xp-e Hew [11]

LED drivers should include the following features; high efficiency, dimming options, direct control of current, over voltage protection, small size and load disconnect. These features are not obligatory, but all of them have applications and benefits for LEDs. However, some properties of LED drivers are obligatory which are over current operations or conditions, repetitive pulsed operations and ripple on the current. This section introduces features, and the obligations [12].

LED drivers are constant current drivers and should have high efficiency. Constant current have to be maintained even if the output voltages changes. As we mentioned LEDs forward voltage changes with respect to temperature and respect to current. LED driver have to be consistent with variable operation of output voltage. High efficiency is a need if input supply is a battery. High power application's drivers have to be efficient; because the excessive power will dissipate on LED driver.

Another feature of led drivers is over voltage protection (OVP). Since the operation is constant current output, current is regulated regardless of the load. If there is an increase in the loads impedance the voltage of the output will increase to high levels. This voltage level can damage LEDs or the electronic components used in driver circuit. Driver performs OVP with different solutions. A popular one is using Zener diode at the output stage of driver, parallel to LEDs. The breakdown voltage of Zener diode will be the maximum voltage of the LEDs (changing due number of LEDs), and it limits the output voltage. Another solution is monitoring the output voltage continuously by resistors. This solution is better because in any failure drivers can directly shut down the operation.

A popular feature of led drivers is dimming. Dimming operation ensures the management of the lumen output of LEDs. This is a popular application for architectural vision in the places light output should be managed in order to change with respect to mood. Another reason is energy saving; by dimming the light when there is no need to much light, energy consumption will decrease. Dimming also applied in order to obtain different colors from red, green and blue LEDs. All of the colored application has to use dim to obtain different colors, because any color different from main colors can only be obtained with mixing these colors. Analog circuits or pulse-width-modulation technique (PWM) can dim LEDs. PWM applications are better than analog applications because of the consistency. The operation mechanism is primarily defining the on-time of the LEDs with in a period. LEDs will light-on in this period and light-off after this period until new cycle starts. Here, frequency is crucial because at lower than 150 Hz; human eye can see this operation as flickering.

The size of the driver is mainly dependent on the working frequency. As higher frequencies used, the size of the driver becomes smaller, but losses start to rise and design start to be an issue. The switch on and off time of LEDs limits the upper bound of switching frequency. Typical LEDs have on/off time about 100 ns, which means the switching frequency can go up to 10 MHz. This value is already extraordinarily high value for typical applications and the trade off of choosing the switching frequency between 100 kHz to 1 Mhz. Another effect for the size is the other components of the drivers. Manufacturers produce ICs including other circuit elements like MOSFET and making the drivers more portable.

The control system of driver changes with respect to applications; peak current control, hysteresis control, average current control methods are some of the used control mechanisms.

Behind the features of drivers, there are obligations that drivers have to adopt; electrical over-stress, repetitive voltages, ripples of the output currents. Electrical over-stress (EOS) is another critical issue for LED drivers. There are sources of EOS; electrostatic discharge (ESD), inrush currents, transient currents. All of these situations occur momentary, but LEDs still can be harmed. In datasheets of LEDs, manufacturers define the maximum drive currents of LEDs, but LEDs can handle over current values than the maximum operating current values. If the forward current increases, current crowding occurs in the junction of LED; which means localized increase of current density. This operation can cause overheat and hot spots on LED die, which provoke electromigration and voids in LED chip [6]. Also, the bond wires of LEDs can damage and act like a fuse; results as an open circuit.

Repetitive waveforms dim the light output of LED. These waveforms are pulse-width modulated (PWM) signals. If the rating of this signal is not carefully assigned, it can also cause electromigration and cause excessive heating in LEDs chips. LEDs manufacturers suggest maximum ratings of LEDs with respect to changing PWM signals.

Finally, the obligation is the ripple on the current waveform of LEDs. Most of the drivers have ripple at the output current waveform changing with a percentage of 5% to 50%; with respect to design considerations of LEDs. First obligation is the maximum value of the current waveform has to be lower than the maximum current rating of LED. The decisive fact is the average value of the current for LEDs characteristics, but the ripple in the current changes the lumen output of LEDs. Also, high ripple cause problems of overheating both on LEDs and passive elements like electrolytic capacitor at the output stage. Overheating affects the life-time of the components.

Standard diodes can handle for surge currents, e.g. rectifier diode with rated operation at 1 A can handle 30 A surge for half a line cycle. LED manufacturers define maximum current ratings, but still LEDs can be driven with little higher currents. This is an unwanted situation because LEDs start to get hotter and there become hot-spots on the LED chip. W white LEDs start to become cooler and finally give blue light by extracting the phosphor plate on it. There are two main methods to obtain DC constant current source; passive or active current control.

2.7.1 Passive Current Control

Passive current control includes a resistor in series with LEDs in order to limit the current. Series resistor does not limit the current it just adjusts the slope of the I-V curve of the LED. Low current loads like low power LEDs frequently used with passive current control. These LEDs have high ESR values so adding another resistor make the current variation less. The applications are like the figure 2.21 one LED can be powered by a voltage source with one resistor, and LEDs can be connected in series or parallel.

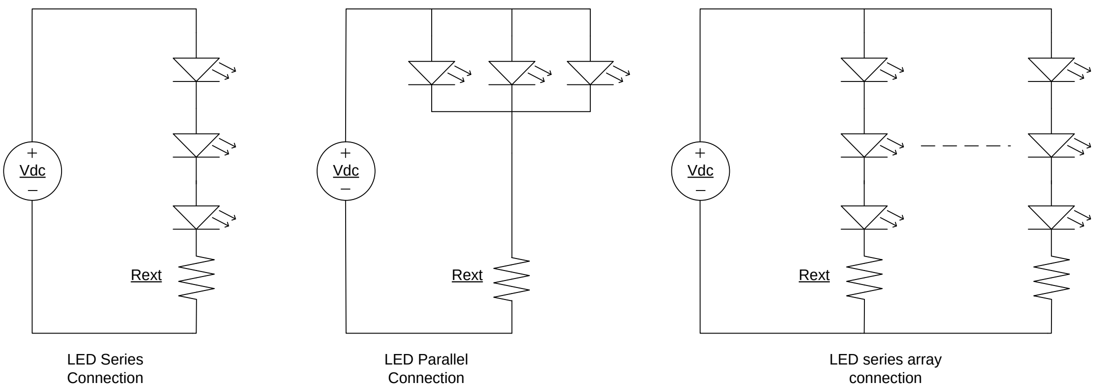


Figure 2.21 Series, parallel and array connection of LEDs

First case is series connection of white low power LEDs. Power Supply will have 12V and the forward voltage drop of 3.2 V and typically operated at 20 mA. The forward current calculated as follow;

$$R_{ext} = \frac{V_{dc} - (V_{f_{LED1}} + V_{f_{LED2}} + V_{f_{LED3}})}{I_f} \tag{2.11}$$

Assuming all the LED forward voltages (V_{fLED1}, V_{fLED2}, and V_{fLED3}) are 3.2 V, and forward currents (I_f) of LEDs are 20 mA, calculated current limiting resistor (R_{ext}) is to be 120 ohms. Now we can look at the variations. If the forward voltages change in the limit of the voltage "bin" given from the manufacturer and the forward voltages are 3.0V, the forward current become 25 mA with a difference of 5 mA. Differently supply voltage can change; if the DC supply's voltage increase by 0.5V, the forward current in the normal case become 25mA. In both cases, the current will be in the range of current limits of LED. If the string number increases or the supply voltage change is more than half volt, the current passing through LEDs will extremely change so that it can go over maximum operation current or the current change will result as the light output change of the LED.

2.7.2 Active Current Control

Power LEDs are different from low power LEDs have low ESR value, which means that passive current control system cannot be maintained. Another issue is the heat dissipation; the current values are 10 times higher than low power devices, and heat dissipation affects the resistance of resistors. Therefore, it is impossible to use passive current limiting technique for PLEDs. Other control type is active current, which uses an active device to limit the current of the LEDs. Linear drivers and dc-dc converters use active devices for their operation.

The control methods only apply for DC power sources; however PLEDs mostly connected to the AC line. Designers use SMPS AC/DC converters for these applications which have a variable output voltage and constant current output. The application of PLEDs are popular in 2000s, but the history of SMPS technology is previous than PLEDs. Here, the main thing is the adaptation of two technology and application. LEDs are efficient devices and become popular with being superior to conventional lamps. In order to save energy, changing the traditional lamps with LEDs will provide over 90% energy saving. Even PLEDs are not better in the manner of efficacy from fluorescents, but they have 5 times longer life-time with respect to them. All of the goodness of PLEDs is related to be driven with correct power electronic device. In any failure all of the advantages of PLEDs return to customer and manufacturer as a big disadvantage.

2.7.3 Standards

A consortium built named *Zhaga*, in order to define LED light terminations and make all of the LED lamps interchangeable. This will make all of retrofit LED modules can be compatible to other ones. Zhaga defines the power supplies for PLEDs as "*Electronic Control Gears"* (ECG) and so the power supply manufacturers (also LED manufacturers) give this name to the PLED drivers. Standards defined for the ECGs; stands for safety and performance.

New standard IEC 61347-2-13 stands for safety requirements and includes protection against electrical shock and protection in a situation of malfunction. The main point is the operation has to be proper to safety extra low voltage (SELV) and involve insulation for high voltages. This means the user or the applier can touch the LED module or LEDs without any risk. Also in case of failure of ECG, easy flammability and no smoke emission must not occur. These converters must contain thermal cut-off circuits.

IEC/EN 62384 [13] standard stands for performance of the application and span the DC or AC supplied ECGs. Standard states that the wattage of the LED module have to be in the limit of 6% - 0% and the tested ECGs have to cover previous standard IEC61347-2-13. This standard standing for performance so has a limitation on power factor correction value of 0.95, if ECG has PF less than this value ECG has to be marked differently. The output current or output voltage has to be in the range of 10% of specified output current or voltage. The impedance of audible-frequencies 400 Hz to 2000 Hz are measured with test systems. The ECG also stand for abnormal conditions; short-circuit and open-circuit load lasting for 1 hour of operation. This standard tests the ECGs for different temperatures with sudden changes, which will show shock resistance. Here, main point is the ECG and the LED module should be optimized for optimum operation.

In order to have CE mark, the ECGs should have EMC and safety standards; EN55015, IEC 61347, IEC 61000-3-2. EN55015 for radiated and conducted radio interference suppression; which give the limits and methods of measurement of the radio disturbance characteristics of electrical lighting and similar equipments.
IEC/EN 61547 stands for EMC immunity requirements for equipment of general lighting purposes. In this standard, the lighting equipments for low voltage supply and batteries introduced by IEC technical committee defined 34 lamps, auxiliaries light devices and luminaries. The immunity requirements are; electrostatic discharges, mains supply disturbances, continuous and transient disturbances radiated and conducted disturbances.

IEC61000-3-2 [14] standards for harmonic standards; which gives the harmonic limitations for the equipment that draws lower than 16A per phase and for the equipment that draws higher than 16A and lower than 75 A IEC 61000-3-12 applies. Standard classifies the equipments into 4 classes with respect to usage, duration of use, power consumption, harmonic spectrum and simultaneity of use of ECGs. Lighting equipments are included within Class C, and this standard gives the exact harmonic limits for the exact harmonics.

CHAPTER 3

POWER SUPPLY TOPOLOGIES FOR LEDs

3.1 Introduction

Electric power is processed and converted to appropriate voltage and current level with power electronic devices for end-user's needs. These devices differentiate with respect to their powers, output types, topologies and qualities. Illuminating engineering society, IES defined power supplies as "*An electronic device capable of providing and controlling current, voltage or power within design limits"* and LED driver is *"A device comprised of power source and LED control circuitry designed to operate a LED package (component), or an LED array (module) or an LED lamp"* [2].

LEDs are devices that work with direct current (DC) power sources. LEDs have to be used by DC power supplies or alternating current (AC) input power supplies. LED driving circuit has limitations to provide correct operation for LEDs. Power supplies have to provide several functions to be compatible with several standards and obligations.DC power sources are generally AC-DC constant voltage output power supplies. Constant voltage power supplies can only be used with active or passive current control to supply constant current for LEDs. Passive control limits the current with resistors and has low cost. Even if, this method is applicable for low power LEDs, still it does not guarantee correct operation. Active control method involves dc-dc converters that convert input dc voltage to proper voltage level for LEDs. These dc-dc converters are basics of switch mode power supplies; which has a switching device to switch on and off the input voltage, and transfer the energy with passive elements to obtain proper output voltage for LEDs.

AC-DC powers supplies use AC mains input and convert the AC voltage to proper DC voltage level for LEDs. Linear regulated power supplies are the first AC-DC power supplies which involve transformers to convert the voltage to a proper level. However, the size and low efficiency of this driver limited the usage of this type of the converter. Conventional AC-DC power supplies convert the AC voltage level to DC voltage with using diode rectifier which also called as AC-DC diode rectifier circuits. Regulated power supplies are switching mode power supplies (SMPS); which use DC-DC stage after diode rectifier stage. SMPSs are power supplies that have conversion of AC-DC-DC, since there is only control in one stage (dc-dc stage) these types of drivers will be named as AC-DC power supplies.

Conventional SMPS, stores the rectified DC voltage in a bulk capacitor. Internal circuitry switches DC voltage on/off at high frequency (10 kHz to 1 MHz) in order to convert the voltage level from one to another. High frequency operation enables the use of small footprint passive devices or transformers, which make a smaller device and a low cost device. SMPS are regulated power supplies and traditionally have constant voltage outputs. Manufacturers provide constant current output SMPS ideal for LED applications. Designers plan SMPS for specific input and output, voltage and current levels. Designers also differentiate SMPS with respect to power capability. Mainly there are two types of SMPS; non-isolated and isolated (with transformer). In addition to properties there are quality issues for SMPSs.

Conventional SMPS have high efficiency but low power factor (PF), high line current distortion, high total harmonic distortion (THD) values, and high noise due switching effects which causes electromagnetic interface (EMI) problems. Power factor is an issue that is necessary for electric energy suppliers, energy distribution companies and manufacturers. Designers improve power factor of SMPS with the use of power factor correction (PFC) circuitry. PFC is implemented within an extra stage or cell or directly within DC-DC stage of SMPS. This circuitry also improves the line current distortions. Other problem is EMI; designers solve with some EMI filter blocks and some passive circuit elements.

LED applications are usually in the range of 0 – 200 Watts; 0-20 Watt is for low-power applications, 20-50W is for mid power and over 50 Watt is for high-power applications. Most of the applications are low and mid-power because of the lighting application requirements.

This chapter involves switch mode power supplies for LEDs. Figure 3.1 shows the stages of SMPSs. There are two types of SMPS; two-stage and single stage SMPS. Sections detail each stage of SMPS with analyzes and examples. First part involves the AC-DC rectifiers, and the AC-DC power supply needs with respect to obligations, safety and application. Next section is the definition part of power, and power quality reasons. Next part is DC drive circuits for LEDs with several dc drive methods. Next section covers the dc-dc stage as a part of SMPS with a short summary, and developments and topologies. This section provides several dc-dc topologies with their working principles and LED application examples. Next part is the other stage of SMPS; here are the PFC cells in the name of two-stage AC-DC power supplies.

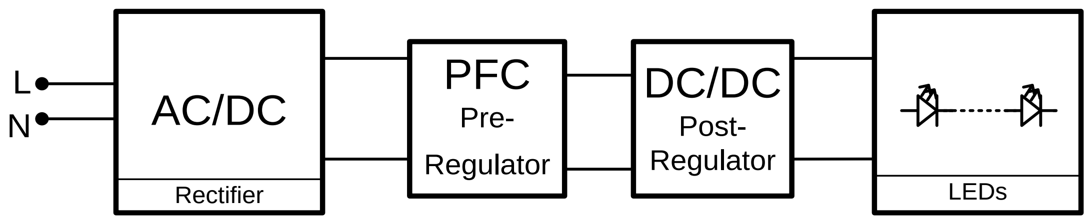


Figure 3.1 Basic schematic of switch mode power supply

This section involves the main PFC applications and the focus point of thesis as single-stage PFC LED drivers. Final part introduces the single-stage converters with historical developments, theoretical problems, advantages, disadvantages and problems. After the survey over various topologies, three special single stage PFC LED drivers will be introduced.

3.2 AC-DC Converters for LED Driver

3.2.1 General

The grid has an electric charge flow by AC. AC is the movement of electric charge in the reverse direction periodically. AC line voltage changes periodically, which defines the frequency of grid. Different countries use line frequencies of 50 or 60 Hz. Grid AC voltage levels changes for different countries, in US low voltage 110 V_{ac} and in Europe high voltage

220 V_{ac} is used.AC power line is defined with sinusoidal function shown in equation 3.1. In the equation instantaneous input voltage is v(t), line voltage RMS value is V, angular frequency is shown with ω and maximum value is V_m.

$$v(t) = \sqrt{2}\,V\sin(\omega t) = V_m \sin(\omega t) \tag{3.1}$$

AC line voltage cannot be used directly for devices working with electronic elements need direct current (DC) supply. DC is the unidirectional flow of electric and can be obtained by power sources like batteries, solar cells or dynamo type electrical machines. DC can be obtained from AC with the use of **rectifiers**. Basic AC-DC rectifier is the uncontrolled rectifier shown in figure 3.2 and 3.3.

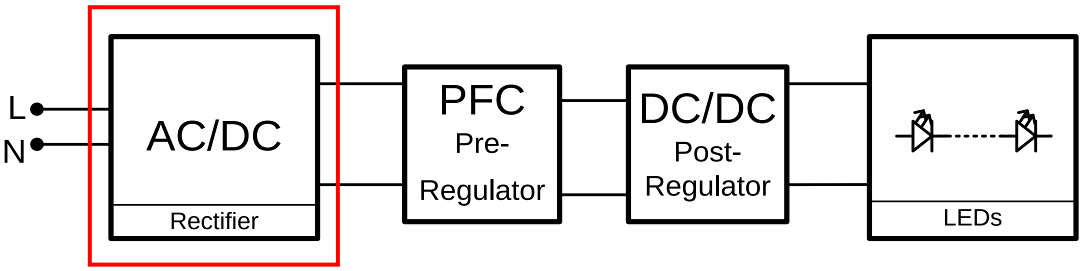


Figure 3.2 SMPS stages, AC/DC rectifier stage

Traditional AC-DC converters can be separated to two main topics; uncontrolled and controlled rectifiers. Uncontrolled rectifiers convert AC line voltage to the DC voltage with the same magnitude, changing the negative polarity of the waveform to positive by using electronic components diode which allows electric charge in one way. Controlled rectifiers contain diodes and controlled devices (thyristors, MOSFETs) rectifying AC to DC line with a complex operation. Controlled rectifiers are not the subject of in this thesis. Thereafter the uncontrolled AC-DC rectifiers just named as AC-DC rectifiers.

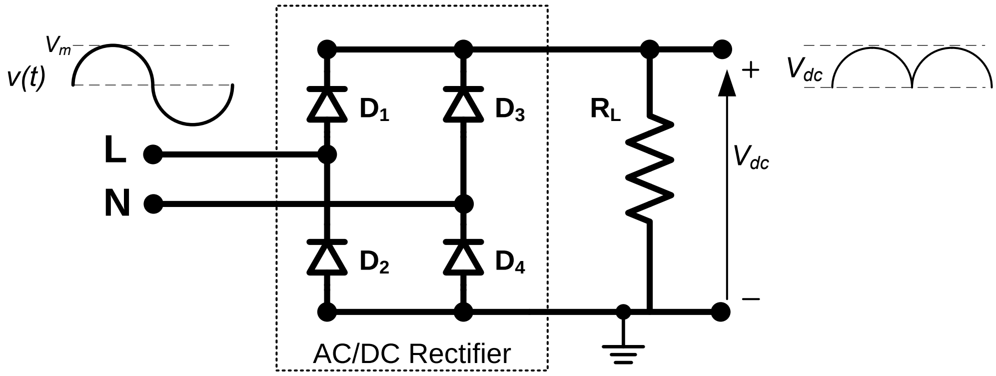


Figure 3.3 Uncontrolled AC-DC rectifier circuit schematic

The operation mechanism of AC-DC rectifier is; in positive AC cycle diodes D_1, D_4 forward biased and D_2, D_3 diodes are reverse biased. For negative AC cycle, the situation is just the opposite. This operation is full-wave rectification and output is DC positive voltage. (If there is just one diode the rectifier is the half-wave rectifier, only conducts the positive cycle of AC) This positive DC voltage is defined with V_{dc} which is changing between 0 and maximum AC voltage (V_m).

Storage (bulk) capacitor (C_o) stabilizes this variable voltage by filtering the voltage. There will be still a voltage ripple, with respect to the value as shown in figure 3.3.

Capacitance value of C_o is a point of trade off, and it changes with respect to the energy that has to be stored for one cycle. For example, grid of 220 V_{ac} and 50 Hz; DC voltage will vary between 0 and 311V. Let's assume there is a DC load of 5W and allowed ripple is 5% on the load. This makes DC voltage, V_{dc} to be maximum 311 V and minimum 280 V on the capacitor. The energy stored in capacitor (E) calculated with equation 3.2;

$$E = \frac{1}{2} C_o V_{dc}^2 \qquad (3.2)$$

The period of the oscillation in DC voltage is twice of the line frequency which calculates to be 100 Hz and a period of 5 ms (period = 1/frequency). For example, an application of 5W; energy need for each cycle is 5W*5ms = 25mJ stored in C_o. The energy storage at high voltage of 309 V (2 V drop of diodes) is 47.75*C mJ by (3.2 where C is mF). Energy need for 278 V is 38.7*C mJ. The difference is the energy can be delivered to the load which is 9.108*C mJ. From calculated energy for load 25 mJ; C is calculated as 2.74 uF.

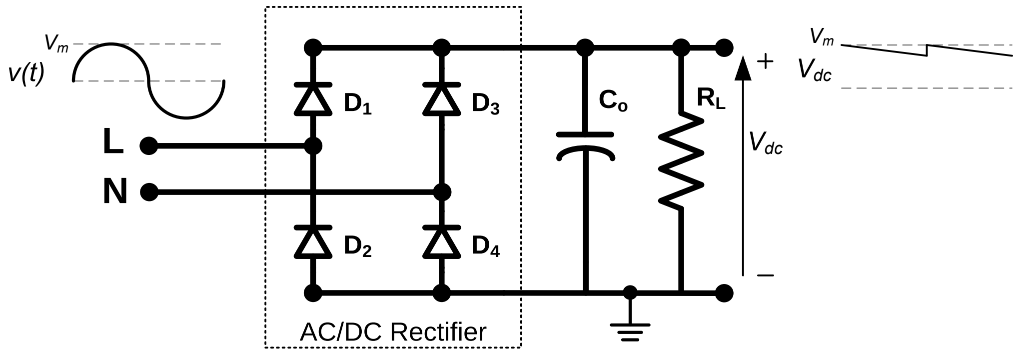


Figure 3.4 AC-DC rectifier with electrolytic capacitor at output

3.2.2 AC-DC Power Supply Special Properties for LED Applications

In this section special applications and properties of SMPS for LEDs will be introduced. These properties stand for safety, application specialty and power quality.

3.2.2.1 AC-DC Power Supply Protection - Lightning

Lightning is one of crucial subject that cause electronic devices to fail. The failure occurs with surge currents on the line current after a lightning occurs. The lightning has an overvoltage effect that drive has 6000 V in input AC parts lasts for 1.5 microseconds. The converters have to be protected against this interruption and best solution for this problem is a semiconductor device; metal oxide varistor (MOV). MOVs pump large amount of currents in high voltages. MOV is an essential solution for protecting a lighting device which has several electronic components on it giving a guarantee of long-life time operation. One drawback is if these events repeat several times MOVs change its property after each lightning effect on AC-DC converter.

3.2.2.2 AC-DC Power Supply Application - Dimming

Traditional light sources usually used with dimmers. This is an architectural and operational need in houses, hotels or restaurants. Even in corridors ballast manufacturers developed specific dimming technologies. This need come from energy saving and the varying the light level with respect to the environment in places. The incandescent lamps can be dimmed easily by cutting some part of AC waveform. The fluorescent lamps can be dimmed with particular dimming protocols and individual electronic converter devices. LEDs have advantages for dimming with respect to other light sources; LEDs can open and close in a short time without degrading its performance or life-time. In this way by applying a PWM signal directly to LEDs, the light output of LED can be changed. A second method is to change the average current of LEDs. IC manufacturers foresee this need and provide the ICs with a PWM input for changing the average output current. Another method is analog method; control circuit compares the output current with a reference voltage. A basic analog circuit having a potentiometer, this reference voltage can be changed, and output current value can be changed.

AC-DC manufacturers and lighting ballast manufacturers define some protocols for dimming systems, in order to produce drivers that can be used in the same system. One of them is DALI, digital addressable lighting interface; which is an 8-bit protocol. This protocol is a digital series interface (DSI) produced by a ballast company, *Tridonic*. Another universal protocol is 1-10V; control signal is a DC voltage changing between 0 to 10 V and the analog voltage level defines the amount of light output. Another digital communication system is DMX 512, which is previously used by stage lighting. Applications with different colors; bring necessity of defining each device a different address. Practically address means that every luminary can be controlled individually. DMX 512 is a RS485 protocol, which have a continuous flow of data divided to 512 – 8 bit data. For example, a multicolor LED product (Also called RGB product which have red-green-blue LEDs) can be used with three addresses; each address is for each color. 8 bit means, 255 different values can be obtained for each color. As a result, this lighting equipment can be lightening up to 16.581.375 different colors.

3.2.2.3 AC-DC Power Supply Protection - EMI

Electromagnetic interface, EMI is a notable fact during the design of power supply. SMPS works with high frequency of hundreds of kHz, which generates a lot of noise. There are two types of noise sources; conducted and radiated. Conducted noise is formed by switching devices that carry high currents. These differentiate in two subjects; normal mode and common mode noise. Normal mode noise is due the different current on the hot line and neutral of ac line input. Common mode is due the different currents on hot and neutral line with respect to the ground wire. Second noise type is radiated noises which is caused by the layouts of current loops. High current loop tracks where current goes and returns; acts like an antenna and radiates noise [3]. Governments and organizations try to limit the amount of noise. The mathematical calculation is hard to performed and extraordinarily complex. There are standard filters for EMI reduction and designers use some practical circuits formed by passive elements.

3.2.2.4 AC-DC Power Supply Power Quality

Power quality regulations and standards stand that the rectifiers have to reach high power factor values. IEC 61000-3-2 standards rule power factor or harmonic reduction, which is biggest restriction point for power supply converters for different classes. Power electronic designers face with several problems; both applying efficient design and meet proper requirements.

Figure 3.5 shows the basic AC-DC offline converter with a large electrolytic capacitor for storage between DC-DC converter and AC-DC rectifier. This electrolytic capacitor has a voltage near the peak value of supply voltage and pulls current at the moment when supply voltage reaches its peak value. This converter has PF value of 0.6.

The poor power factor value does not ruin the operation mechanism of converter. The critical problem is for the energy supplier companies. The converters having poor power factor has an effect on power lines; the converter misdirects the line as pulling current without dissipating it. The pulled current fed back in the next cycle so the current meter does not see this power and the customer do not pay for this amount of energy. Governments define standards for power factor in order to protect the distribution companies.

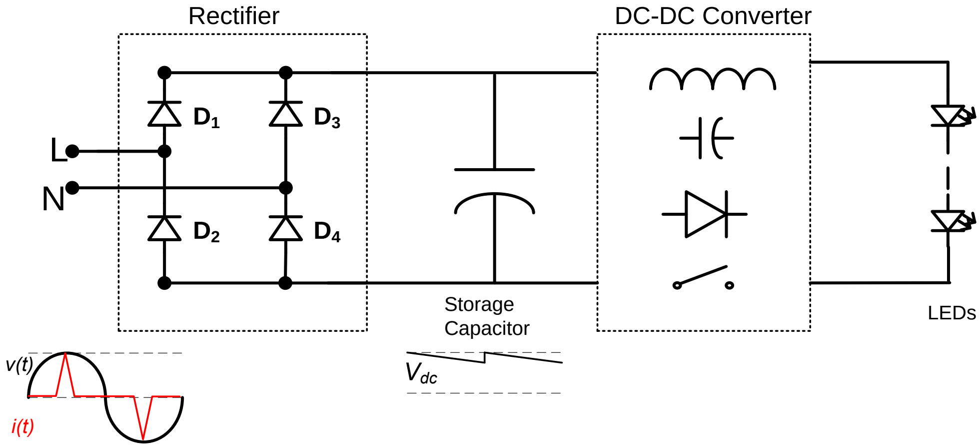


Figure 3.5 AC-DC offline converter schematic

3.3 Power Factor Correction

This section covers the power quality terms, power factor and distortion factors with their analytical calculations

Power factor (PF) is a non-unit parameter, changing between 0 and 1. In AC systems the current is dependent on the load. The equation 3.1 shows the AC line voltage and equation 3.4 shows the line current. In the equation, input line current is i(t), RMS value of line current is I, the peak value of input line current is I_m, and phase angle is φ.

$$i(t) = \sqrt{2}\, I \sin(\omega t - \varphi) = I_m \sin(\omega t - \varphi) \tag{3.3}$$

This definition is valid if the load is linear; resistive, capacitive or inductive. Then the PF is the ratio between the real power in Watts and apparent power in Volt-Ampere; from the power vector diagram; $P = S\cos\varphi$.

$$PF = \cos\varphi = \frac{\text{Real Power}}{\text{Apparent Power}} \tag{3.4}$$

PF value calculation changes if the input current is distorted. First the distorted input current is defined with first harmonic i_1, in which RMS value of input current is I_1, peak current value is I_{m1} and phase angle of first harmonic is φ_1.

$$i_1 = \sqrt{2}\, I_1 \sin(\omega t - \varphi_1) = I_{m1}(\omega t - \varphi_1) \qquad (3.5)$$

The value displacement power factor (DPF), total harmonic distortion of input line current (THD_i), total harmonic distortion of input line voltage (THD_v) and power factor (PF) defined as;

$$DPF = \cos \varphi_1 \qquad : \% \qquad (3.6)$$

$$THD_i = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \qquad : \% \qquad (3.7)$$

$$THD_v = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \qquad : \% \qquad (3.8)$$

$$PF = \frac{DPF}{\sqrt{1+THD^2}} \qquad : \text{non-unit: } 0 < PF < 1 \qquad (3.9)$$

In the previous equations; amplitude of the n-th harmonic of line current is I_n, amplitude of the n-th harmonic of line voltage is V_n.

Practically power factor means; how close is the input current waveform to the input voltage waveform. Power factor correction (PFC) is the phenomena that an extra circuit or the converter tries to show the output of the power converter like a resistor [3, pg117].

3.4 DC Drive Circuits for LED

3.4.1 Linear Drivers

The basic drive circuit for LEDs is linear DC drivers which involve a voltage regulator like LM317 or an op-amp and active switch. These devices are used to be as current-sink or current-source circuits in order to comply constant current output for LEDs. These drivers are preferred just for easiness of application and no EMI radiation. In fact, these devices have some limitations; LED voltage has to be smaller than the supply voltage and voltage difference between supply and LEDs have to be low. This voltage will drop on the active device, and this device dissipates this as excess power. Linear drivers are inefficient solutions because of their operation principle. Another concern is the power dissipation radiates with heat and this can be transferred with a bulk heat-sink. If the supply voltage and led-voltage have a significant difference, the circuit cannot be applied because of heat and device size conditions.

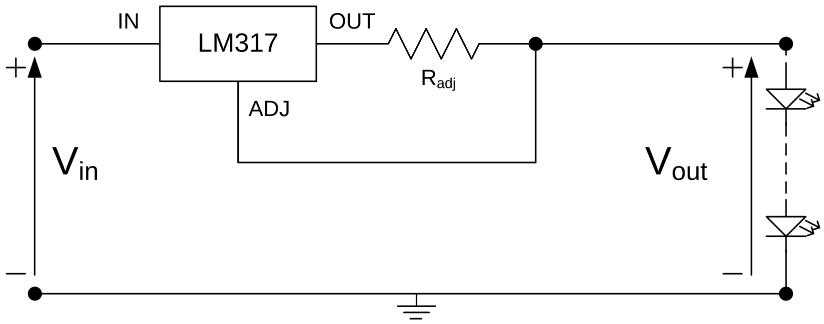


Figure 3.6 Linear driver with voltage regulator IC for LEDs

Designers and researchers focus on switching drivers for DC-DC and AC-DC converters. [6,23-25]

3.4.2 DC-DC Converters

DC-DC converter is a power converter that converts dc energy source from one voltage level to another. *"DC-DC converter is also known as a chopper or switching regulator, average* *output voltage is controlled by varying the conduction time of switch"* [15] The DC-DC converters can be designed with regulated output voltage. Especially for LED drivers the converters have regulated output currents. This section introduces a short summary of these electronic circuits.

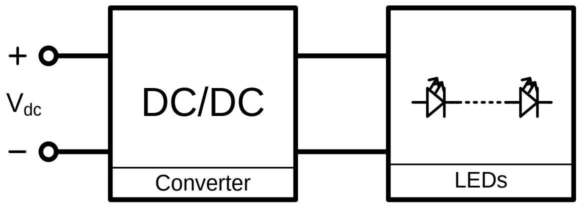


Figure 3.7 DC-DC converter model for LEDs with DC input voltage

DC-DC converters have various applications in industry, digital cameras, cell phones, computers and lighting. In this wide application area; there are over 500 developed topologies for DC-DC converters. Various topologies of DC-DC converters can be differentiated in six generations [16].

First generation is the classical or traditional converters differentiating with respect to converter purpose and power efficiency. Second generation converters, work in two-quadrant and fourth-quadrant and have power capacity of 100 to 1000 Watts. Third generation of converters; switched component converters used in high powers of 1000 Watts. Fourth generation converters are the converters with new switching technologies. There are two main groups; zero-voltage switching (ZVS) or zero-current switching (ZCS). This switching technology is soft-switching technique, mainly involves the application of resonance switching using the resonance characteristics of circuit. Fifth generation of converters is synchronous rectifiers with low voltage and high current capability. These converters have high power transfer efficiencies. Sixth generation of converters are multi elemental resonant converters; used in military and industrial applications.

In various applications of LEDs bring out the need of different topologies of DC-DC converters. DC-DC converters have constant voltages in their output but LED needs constant current DC power source. Designers adopted DC-DC converters as constant current converters by adding a shunt resistor series to the LEDs and adjusting the output level with respect to this shunt resistor. Today PLEDs most popularly applied in low and mid powers between 0 – 50 Watts. The developments of the LED technology and the demand for various kinds of lighting applications show that in short-time period LEDs will be popular also in the high-power range. Also, integrate circuit (IC) manufacturers start to produce led-driver ICs for different topologies and powers. This way the circuit designers can easily implement DC-DC LED drivers for their applications.

DC-DC converters are a necessity for LEDs to have regulated output and high power efficiency. Typically the first generations of converters used because of easiness of application and low cost. First generation converters differentiate in six parts with respect to the developments and efficiencies. First part is the *fundamental converters* are Buck (Step-Down), Boost (Step-Up) and Buck-Boost (Step-Up and Step-Down) converter. These converters have limited conversion energies and power densities due parasitic. Transformer-type and developed converters have a wide range of the output voltage and power. Second part is the *converters with transformers*; Flyback, Forward, Push-Pull, Half-Bridge, Bridge and Zeta Converter. These converters have transformers and isolate the input and output circuit. Transformers add an extra property of changeable voltage gain with the ratio of transformer windings and isolation. Third part are the developed converters; P/O (positive output) Luo-converter, N/O (negative output) Luo-converter, Double output Luo converter, Cúk converter, Single-ended primary inductance converter (SEPIC). These converters have more components, having less output voltage ripple than the previous converters. Fourth part is the voltage lift converters (VL); applied to the developed converters and voltage transfer gain is increased. Fifth part is super-lift (SL) converters, and sixth part is ultra-lift (UL) converters. SL and UL converters also applied to developed converters, and they improved the voltage transfer gain.

3.4.2.1 Fundamental Converters

Most of the LED drivers are fundamental converters of first generation DC-DC converters. DC-DC converters for LED drivers are popularly low power and low cost. Next section involves the fundamental converters for LED applications. In this chapter, the performed analyzes are at steady-state conditions and switching devices are ideal. Converters operation mode are continuous conduction mode (CCM).

In these three converters the variable in the equations are; maximum inductor current (I_{max}), minimum inductor current (I_{min}), duty cycle (D), inductor (L), switching time period (T_s), peak-to-peak current value of inductor (ΔI), supply voltage (V_s), output voltage (V_o), and switching frequency (f).

3.4.2.1.1 Buck Converter LED Drivers

Buck converter, step-down converter, converts the input voltage into output voltage, which is less than the input voltage. Buck converter circuit schematic is shown in figure 3.8.

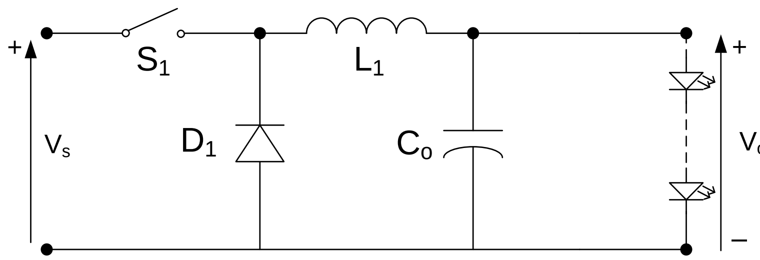


Figure 3.8 Buck converter basic schematic

The operation principle of buck converter is transferring energy by inductor (L_1), to the output capacitor (C_o) and load as LEDs by using switch (S_1) and diode (D_1). The circuit operation can be divided into two modes. First mode (Mode1) starts with the switch is on, inductor starts to store energy and also output capacitor and LEDs pull current directly from the source. Second mode (Mode 2) starts when switch is off, and inductor releases its energy to the load. This two modes are valid for continuous conduction mode (CCM) operation which we investigate the converters. For discontinuous conduction mode (DCM) operation, there is a third mode; switch is off and diode is reversed biased no current flows from the inductor.

Mode 1: Switch on, Diode off (diode reverse biased)

The current on the inductor increases with equation 3.10

$$\frac{\Delta I}{\Delta T} = \frac{I_{max}-I_{min}}{t_1} \quad \gg \quad \frac{I_{max}-I_{min}}{D*T_S} = \frac{V_S-V_O}{L} \qquad (3.10)$$

V_s-V_o is the voltage drop on the inductor during on-time. ΔT is the on-time period (0,t1) and ΔI is the difference between, inductors maximum current and minimum current. The on period of the switch is defined with duty cycle (D). The moment $t_1 = D*T_s$; is the time of switch position changes and mode 2 starts.

Mode 2: Switch off, Diode on (diode forward biased)

At moment t1; switch is closed, and the inductor start to decrease with the following equation. The voltage drop on inductor is equal to negative of output voltage ($-V_o$).

$$\frac{\Delta I}{\Delta T} = \frac{I_{min} - I_{max}}{t_2 - t_1} = \frac{I_{min} - I_{max}}{1 - D \ * T_s} = \frac{-V_o}{L} \qquad (3.11)$$

The voltage equation of the converter can be found from the steady state conditions. Figure 3.9 shows the voltage and current waveform of the inductor. Another way is to calculate by using the inductor ripple equations 3.10 and 3.11. The change in the inductor current is equal and gives voltage ratio of buck converter.

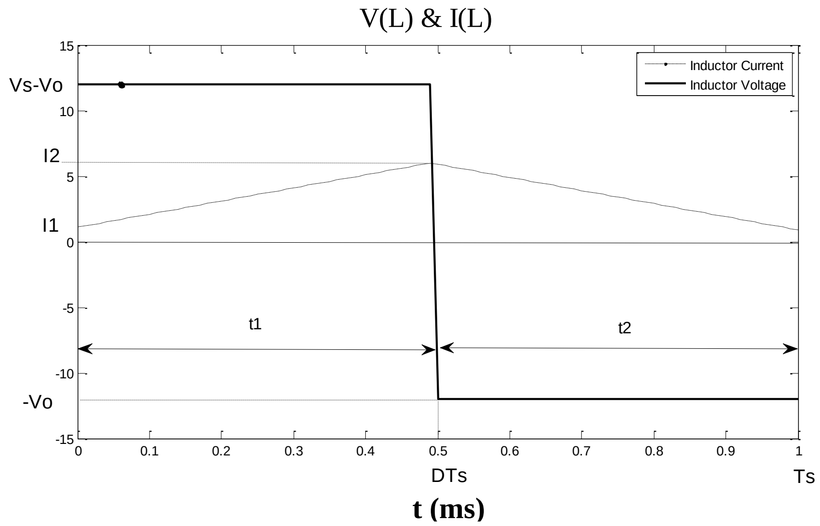


Figure 3.9 Buck converter inductor current and voltage waveforms

$$\frac{(V_S - V_O)DT_S}{L} = \frac{V_O(1-D)T_S}{L} \qquad \gg \qquad \frac{V_O}{V_S} = D \qquad (3.12)$$

By using the equations, the current ripple can be obtained as:

$$\Delta I = \frac{V_s D(1-D)}{f\ L} \tag{3.13}$$

The steady-state conditions state that the total current change of the capacitor is zero in one switching cycle. Equation 3.14 shows the voltage ripple:

$$\Delta V_c = \frac{D(1-D)V_s}{8CL} * T^2 \tag{3.14}$$

In buck converter, the key point is the inductor current is equal to load current and which means that it is the LEDs current in LED driver. So the buck converter is unique among the other converters. There is no need for electrolytic capacitors, because there is no need for voltage regulation. This section shows an implementation of buck based LED drivers. The drivers can have different input voltage ranges between 3.3 V to 75 V and include internal MOSFET. If the converters supply voltage can be matched with ICs supply voltage, there is no need of extra circuit to supply the ICs. So extra power loss is decreased. Also, this IC with high input voltage range is capable to drive switching elements with high voltages, which increases MOSFETs current capacity.

Table 3.1 Buck based LED driver application

Feature	Value
Supply Voltage	36 V
Supply Voltage Tolerance	10%
LED Type	Cree Xlamp XP-E
LED Voltage (@500mA)	3.2 V
LED Voltage maximum	3.5 V
LED String	8#
LED Current	500 mA
LED Current Ripple	10%
Switching Frequency	250 kHz

In this application the output voltage is 3.2V*8 = 25.6 V but the bad conditions should be in mind by having mistakes in LEDs the output voltage should increase up to 28 V. R_{on} is the resistor that defines the converter working frequency. The converter operates in CCM mode to have a lower size of the inductor and low-cost. Choosing inductor current ripple is a trade-off; lower ripple is better operation but higher inductance value. In this driver the ripple is 30% which means +/- 15% change of current; LEDs current will increase up to 575 mA.

The limitation for current ripple is the LEDs maximum operating current, if LED has a maximum operating current of 500mA; this type of circuit will degrade the LED life-time. The LED for the circuit has a maximum operating current of 1A which is proper for this driver circuit. IC has a structure of creating a floating drive voltage for MOSFET gate drive and uses this bootstrap circuitry and uses a bootstrap capacitor (C_b). Sense resistor, R_{sns} defines the average current value of the LEDs. The output diode should be capable of handling reverse voltages and the current. The diode operating current can be calculated by duty time of diode multiplied by output current.

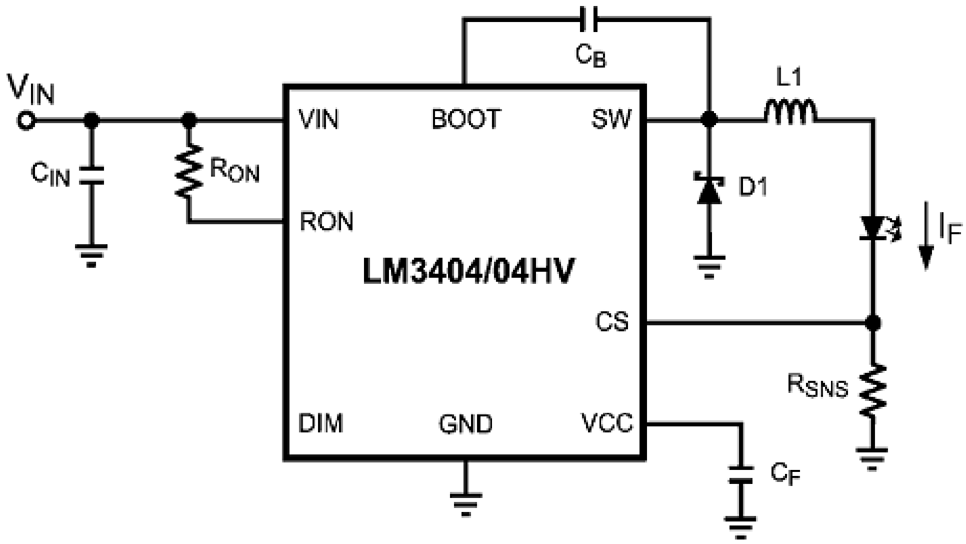


Figure 3.10 LM3404HV application schematic for buck based LED driver [17]

3.4.2.1.2 Boost Converter LED Drivers

Boost converter, step-up converters, convert the input voltage to output voltage that is higher than the input voltage. Boost converter circuit elements just use the same circuit elements of buck converter with a new arrangement of the circuit shown in figure 3.11. Converter elements are energy transfer element inductor (L_1), switch (S_1), diode (D_1) and energy storage element capacitor (C_o).

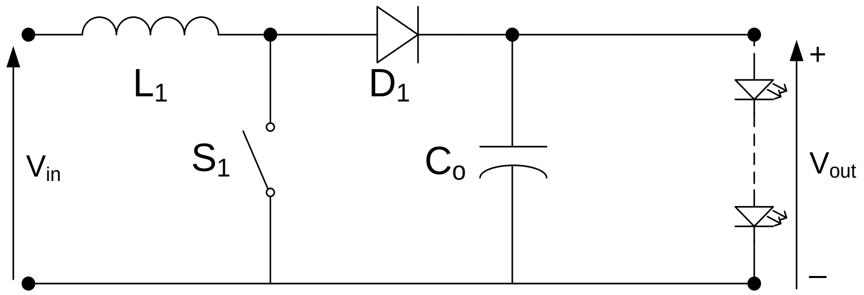


Figure 3.11 Boost converter basic schematic

Boost converters have the advantage of easy design and high efficiencies. Also, input current can be continuous so the EMI standards can be easily satisfied. The switching device and current sensing circuit element use same ground; which provides better accuracy. However, boost converters for LED drivers have disadvantages; output voltage or current is pulsating so large capacitances have to be used. This large capacitance complicates the PWM dimming which is essential for LED application. Another drawback is; if there become a short circuit, switch has no effect and also for high input voltages; surge currents drive LEDs which damage them. Still boost converters can be implemented with caring these situations.

The operating principle of the converter is transferring the stored energy on L_1 from supply to C_o and load (LEDs). The circuit operation can be divided into two modes. First mode (Mode1) starts with the moments that switch turns on. The inductor starts to store energy and LEDs pull current from output capacitor. Second mode (Mode2) starts when switch is off, inductor releases its energy to the load.

Mode 1: Switch on, Diode off (diode reverse biased)

Equation 3.15 shows the increase in the inductor current:

$$\frac{\Delta I}{\Delta T} = \frac{I_{max}-I_{min}}{t_1} = \frac{I_{max}-I_{min}}{D*T_S} = \frac{V_S}{L} \tag{3.15}$$

Mode 2: Switch off, Diode on (diode forward biased)

In the second mode switch is off and inductor supply the load and charge the capacitor, the inductor current decrease with;

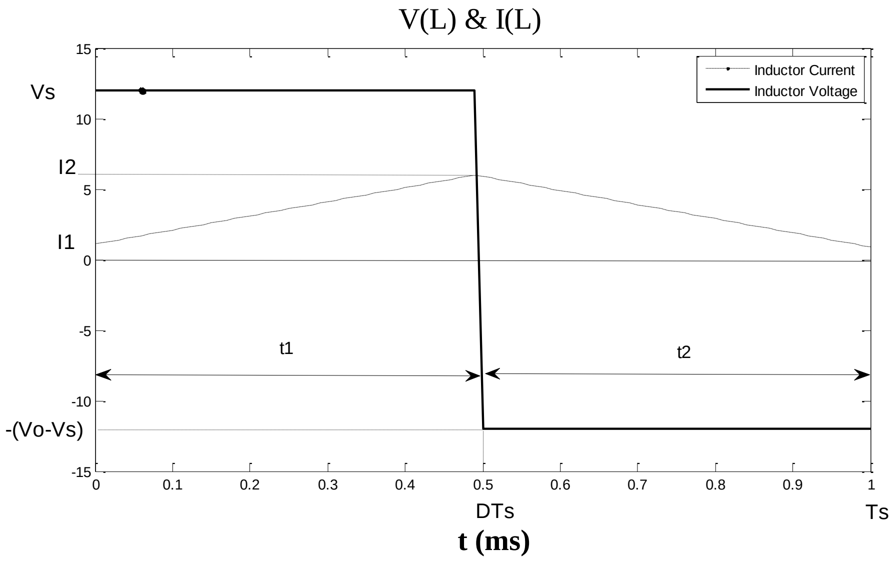


Figure 3.12 Boost converter inductor voltage and current waveform

$$\frac{\Delta I}{\Delta T} = \frac{I_{max}-I_{min}}{t_2-t_1} = \frac{I_{max}-I_{min}}{1-D\ \ T_S} = \frac{V_S-V_O}{L} \tag{3.16}$$

By equation the two equations 3.15 and 3.16 the voltage relationship of the boost converter can be obtained;

$$\frac{V_S D T_S}{L} = \frac{(V_O-V_S)(1-D)T_S}{L} \gg \frac{V_O}{V_S} = \frac{1}{D} \tag{3.17}$$

The minimum inductance value (L_{min}) defines the condition to operate in CCM mode. If the minimum current value is non-zero, converter will work in CCM mode.

$$L_{min} = \frac{D(1-D)^2}{2} T_s \frac{V_o}{I_o} \tag{3.18}$$

This section covers an example of the boost converter based LED driver. Applications like backlighting and street lighting; products have lots of LEDs. Since the correct operation is to connect the LEDs serially, drivers have to deliver high voltage outputs for LEDs. The best solution for these products is boost converters.

The example boost converter is a backlighting solution with high brightness LEDs; FAN5343 is the IC for boost control. This IC involves internal MOSFET (special DMOS MOSFET from Fairchild) and a schottky diode.

Table 3.2 Boost converter application details

Feature	Value
Supply Voltage	3.3V
Supply Voltage Tolerance	10%
LED Type	Nichia NS2W157R
LED Voltage (typical)	3.2 V
LED String	3#
LED Current	20 mA
LED Current Ripple	10%
Output Voltage Range	8 – 18 V
Supply Voltage	3.3V

The IC has overvoltage, over-current protection and thermal protection. The application is a low power of 500mW. IC is capable of digital dimming with the use of *EN* input by a single wire. Current set resistor (R_{set}) is used to define the output current which refers to the internal voltage applied to R_{set}. The current ripple of inductor defines the inductance value of inductor which is 10 uH in this case.

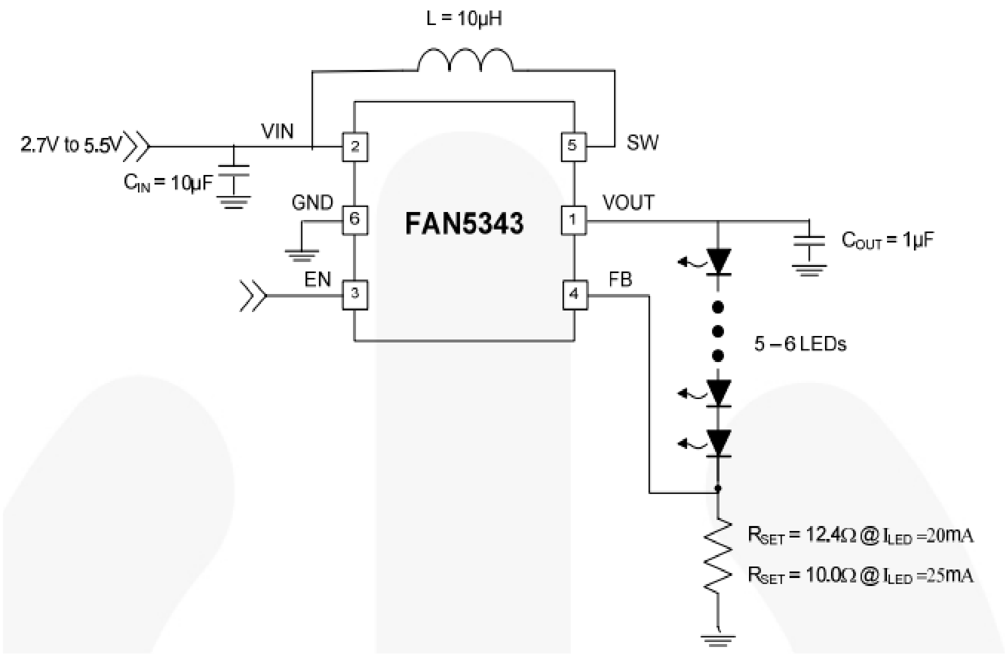


Figure 3.13 FAN5343 application diagram

3.4.2.1.3 Buck-boost Converter LED Driver

Buck-Boost converter is a DC-DC converter that converts the input voltage to a voltage level that either lower or higher than the input voltage. Buck-boost converter stands for applications where the input voltage varies in a wide range such that LEDs output voltage becomes lower or higher than the input voltage. Buck-boost converter delivers negative output. The converter schematic is shown in figure 3.8. The operating principle of the converter is transferring the stored energy on inductor (L_1) from supply to capacitor (C_o) and load (LEDs) similar to other converters. The other converter elements are switch (S_1) and diode (D_1) that transfer the energy. The circuit operation can be divided into two modes. First mode (Mode1) starts with turning on the switch. The inductor stores energy, LEDs pull current from the source. Second mode (Mode2) starts when switch is off. Inductor releases its energy to the load.

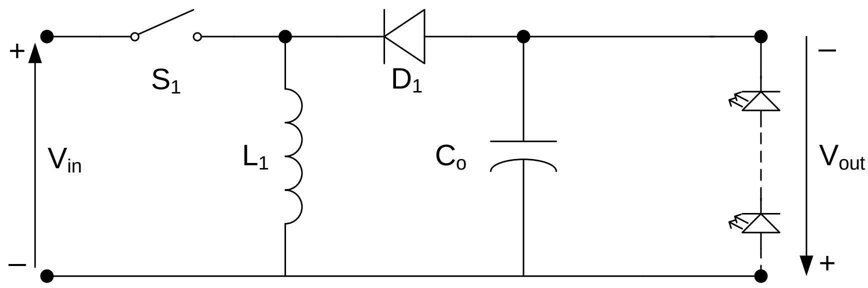


Figure 3.14 Buck-Boost converter basic schematic

Mode 1: Switch on, Diode off (diode reverse biased)

The inductor current increases with the equation 3.26

$$\frac{\Delta I}{\Delta T} = \frac{I_{max} - I_{min}}{t_1} = \frac{I_{max} - I_{min}}{DT_s} = \frac{V_s}{L} \tag{3.19}$$

Mode 2: Switch off, Diode on (diode forward biased)

$$\frac{\Delta I}{\Delta T} = \frac{I_{max} - I_{min}}{t_2 - t_1} = \frac{I_{max} - I_{min}}{1 - D \ *T_s} = \frac{-V_o}{L} \tag{3.20}$$

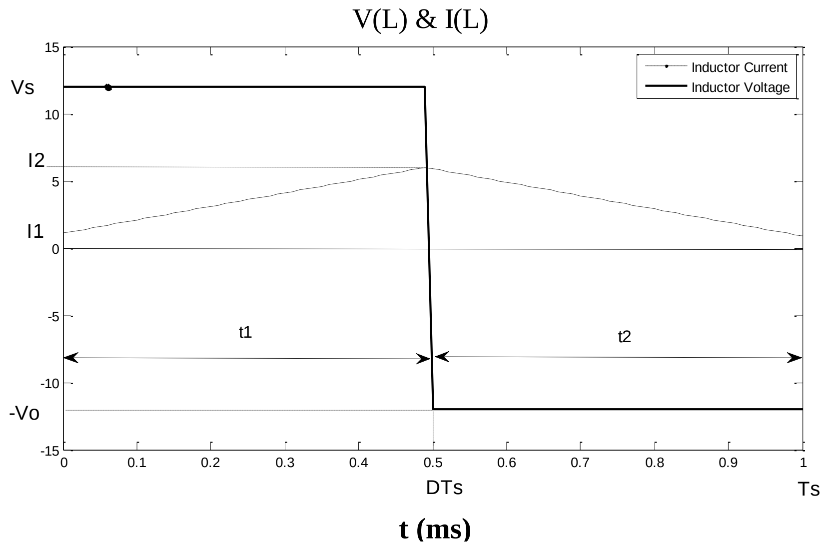


Figure 3.15 Buck-Boost converter inductor voltage and current waveforms

By equating the two equations 3.19 and 3.20 with respect to the current change, the voltage relation of the driver can be obtained.

$$\frac{V_S D T_S}{L} = \frac{(-V_O)(1-D)T_S}{L} \quad = \gg \frac{Vo}{Vs} = -\frac{D}{(1-D)} \tag{3.21}$$

Also, switching period or working frequency can be found with given inductor current ripple ΔI with using the equation 3.22.

$$T = \frac{1}{f} = \frac{\Delta I\ L\ (V_O - V_S)}{V_O V_S} \tag{3.22}$$

The example is a buck-boost LED driver, which uses IC *Texas Instruments* product; IC LM3421. [18] Table 3.3 details the converter properties. Here, the basic parameters obtained for the buck-boost application. The input voltage can change, or the converter can be used with different supplies having different voltages. The output voltage is 22V, and the resistances of LEDs are 2.8 ohms totally. Equation 3.23 and 3.24 calculates the duty cycle limits; minimum duty cycle (D_{min}) and maximum duty cycle (D_{max}) with respect to minimum supply voltage (V_{s-min}) and maximum supply voltage (V_{s-max}).

Table 3.3 Boost converter application details

Feature	**Value**
Supply Voltage	12 - 48 V
Supply Voltage Tolerance	1%
LED Type	Lumileds Luxeon A
LED Voltage @500 mA	2.75 V
LED String	8 #
LED Current	500 mA
LED Resistance	350 mΩ
LED Current Ripple	10%
Switching Frequency	500 kHz

$$D_{min} = \frac{Vo}{Vo + V_{S-max}} \quad = \frac{22}{22+50} = 0.31 \tag{3.23}$$

$$D_{max} = \frac{Vo}{Vo + V_{s-min}} \quad = \frac{22}{22+12} = 0.64 \tag{3.24}$$

Converter switching frequency set by set resistor (R_t) and set capacitor (C_t) calculated to be 49.9kΩ and 1nF. LED current is set by the sense resistor (R_{sns}) which is compared with an internal voltage of 100 mV and calculated to be 0.2 Ω. Inductor is calculated with respect to the ripple on the inductor. In buck-boost converter inductor current is not equal to LED current like buck converter so it allows higher ripple. Here, current ripple on inductor is selected 350mA. Designer guarantees the CCM operation by using maximum input voltage and minimum duty cycle value (3.23).

$$L = \frac{V_S\, D}{\Delta if} \tag{3.25}$$

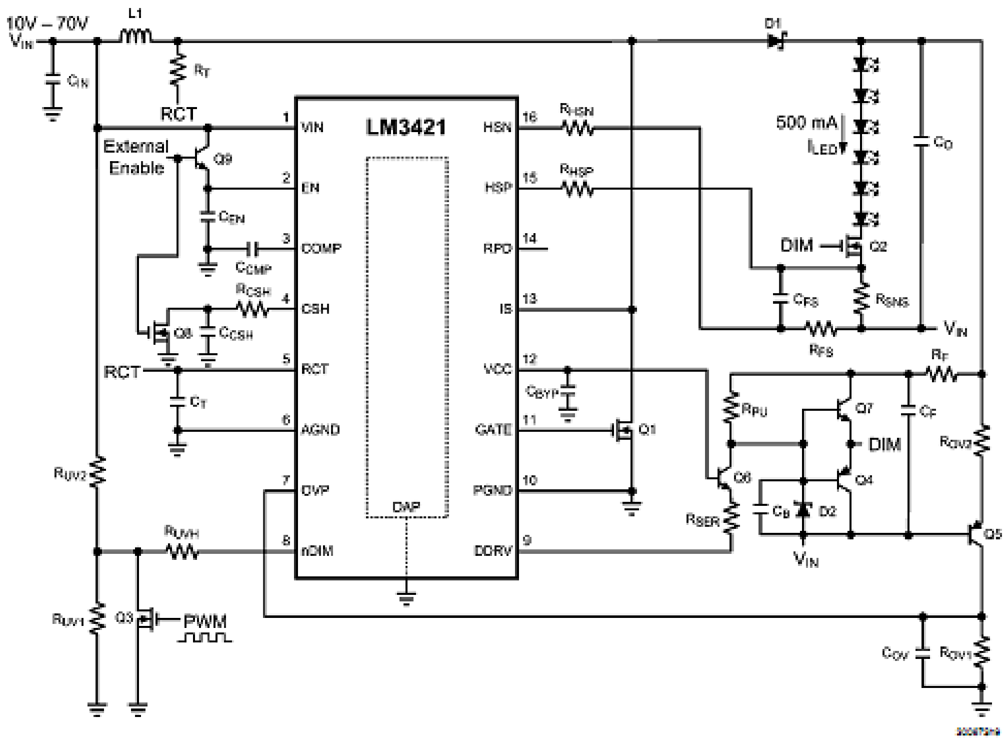


Figure 3.16 Buck-Boost LED driver application circuit [18, pg39]

Inductance value is 85uH; the standard value of inductance is 82uH which makes inductor current ripple 351 mA. In order to calculate output capacitance the LED current ripple has to be selected. In the application 10 percent of LED current ripple counts to 50mA. In the following equation, I_{LED} denotes LED current, r_D denotes LED equivalent series and Δi_{LED-pp} denotes LED current peak-to-peak ripple.

$$C_o = \frac{I_{LED} D}{r_D \Delta i_{LED-pp} f} \tag{3.26}$$

Here, output capacitance (C_o) is 3.21 uF, in which 3.3uF is the closest standard value. The IC has various properties; designer can set the overvoltage and under voltage parameters, that converter stops the operation. Designer set the parameters for the hysteresis control of IC. The figure 3.16 illustrates the layout of the converter.

3.4.2.2 Transformer-Type Converters

Second part are the *converters with transformers*; Flyback, Forward, Push-Pull, Half-Bridge, Bridge and Zeta Converter. These converters have transformers and isolate the input and output circuit. Transformers add an extra property of changeable voltage gain with the ratio of transformer windings and isolation. However, it introduces several drawbacks and extra circuit designs.

3.4.2.2.1 Flyback Converter

Flyback converters are popular dc-dc converter topologies with respect to its uncomplicated design and low cost. Flyback converter is the developed form of buck-boost topology and has the same principle of operation as it converts the input voltage to output voltage that is either low or high than the input voltage. Additional transformer provides isolation and wide range of transfer ratio. It can also provide more than one outputs with different voltage and current levels.

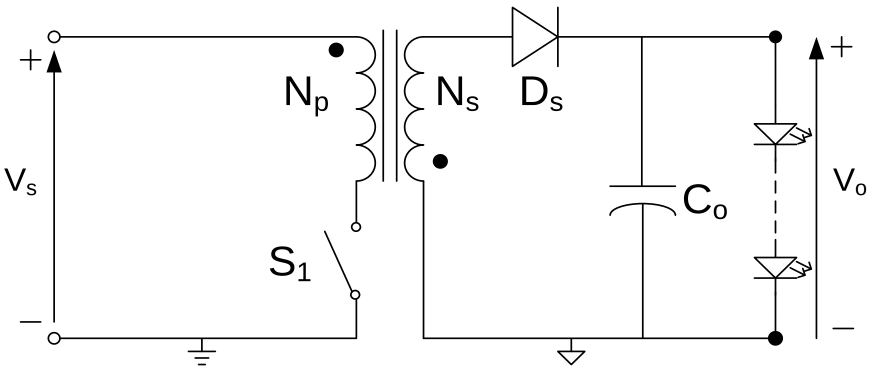


Figure 3.17 DC-DC Flyback converter basic layout

Figure 3.17 shows the fundamental layout of flyback converter. Flyback converter is similar to other converters; transfers the stored energy with the flyback transformer to output at every switching cycle. It uses electrolytic capacitors to store energy. Converter can be analyzed in two modes. First mode (Mode1) starts with the switch is on; diode Ds is reverse biased and transformer' s magnetizing inductance start to store energy and LEDs pull current from capacitor. Converter's fundamental components are transformer magnetizing inductance (L_m), transformer with two windings as primary winding (N_p) and secondary winding of transformer is (N_s), output diode (D_o), switch (S_1) and output capacitor (C_o).

Mode 1: Switch on, Diode off (diode reverse biased)

The magnetizing inductor current increases in this time period and change in the current (ΔI) within a time period (ΔT) is shown with the equation 3.26.

$$\frac{\Delta I}{\Delta T} = \frac{I_{max} - I_{min}}{t_1} = \frac{I_{max} - I_{min}}{D * T_s} = \frac{V_s}{L_m} \tag{3.26}$$

Second mode starts when the switch moves to off position. Following this operation, flux flowing through the flyback transformer reverses its direction. The polarity at the secondary side of transformer reverses and the diode is forward biased following this operation. Here, the flux on the transformer flies back, which gives the name of the converter. The stored energy is released to the secondary side; feeding the output capacitor and load.

Mode 2: Switch off, Diode on (diode forward biased)

$$\frac{\Delta I}{\Delta T} = \frac{I_{max}-I_{min}}{t_2-t_1} = \frac{I_{max}-I_{min}}{1-D \ *T_s} = \frac{V_o\frac{N_p}{N_s}}{L_m} \quad (3.27)$$

The equations 3.26 and 2.27 give the voltage relation of converter with respect to current change on the flyback magnetizing inductance.

$$\frac{V_s D T_s}{L_m} = \frac{(V_o*\frac{N_p}{N_s})(1-D)T_s}{L_m} \quad \gg \frac{Vo}{Vs} = \frac{D}{(1-D)} \quad \frac{\mathrm{N_s}}{\mathrm{N_p}} \quad (3.28)$$

Flyback converter has an advantage of a wide range of transfer ratio; which changes by varying the duty cycle and the turn ratio of flyback transformer. Similarly to other converters, Flyback converter works in DCM or CCM mode of operation. DCM mode is preferred because the transformer is totally demagnetized at the end of the operation. DCM mode guarantees that there will not be a saturation problem on the core. However, it requires higher values of inductance, and high peak currents occur in transformer. Second mode of operation is CCM mode; in which transformer current is continuous for switching period. Inductance value and peak current values are lower. However, switch turns-on during positive current, which require, turn-on speed, and turn-off speed. Otherwise, efficiency decreases and heat dissipates on switching element.

The output voltage or current can be regulated by using an optocoupler. Optocoupler transfers the voltage from the secondary side to the primary side with isolation. Regulation can also be performed by primary current control techniques.

3.4.2.2.2 Forward Converter

Forward converter is another transformer type converter; uses a transformer which isolates input and output. This converter is a superior solution for mid power applications (100 W – 200 W). The output voltage can be negative output and by changing the transformer primary to secondary turn ratios a wide range of output can be obtained. The operation mechanism is similar to other converters; it can be investigated in two operation modes. Mode one starts with the switch moves to on position, diode D_1 is forward biased and D_2 diode is reserved for the free-wheeling period.

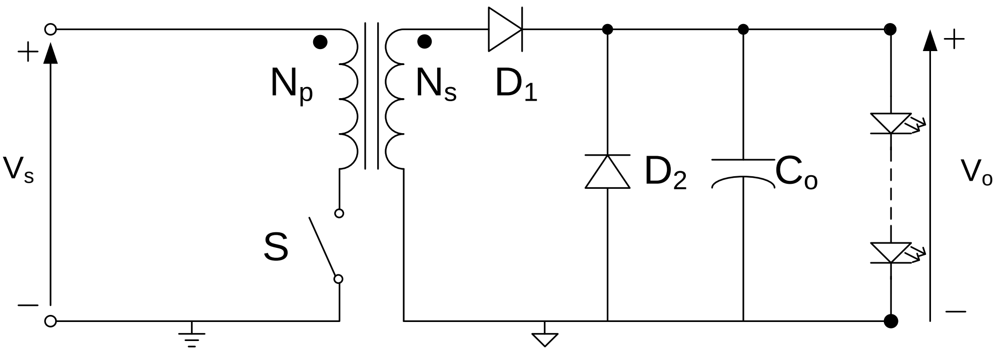


Figure 3.18 DC-DC Forward converter basic layout

The transformer acts like an inductor and transfers the current to output and capacitor. Unlike to flyback converter; here transformer does not store much energy on it.

Mode 1: Switch on, Diode D1 on

$$\frac{\Delta I}{\Delta T} = \frac{I_{max} - I_{min}}{t_1} \qquad >> \frac{I_{max} - I_{min}}{D * T_S} = \frac{V_S \frac{N_S}{N_P} - V_o}{L_m} \tag{3.29}$$

Second mode starts when the switch moves to off position and diode, D_1 is reverse biased and load is fed by the output capacitor.

Mode 2: Switch off, Diode on (diode forward biased)

$$\frac{\Delta I}{\Delta T} = \frac{I_{max} - I_{min}}{t_2 - t_1} \qquad = \frac{I_{max} - I_{min}}{1 - D \ * T_S} = \frac{V_o}{L_m} \tag{3.29}$$

The equation 3.26 and 3.27 states the current change of the inductor. Equation 3.30 gives the voltage relation of the converter.

$$\frac{(V_S\frac{N_S}{N_P} - V_o)D}{L_m} = \frac{V_o(1-D)}{L_m} \gg \frac{Vo}{Vs} = \frac{N_s}{N_p} D \tag{3.30}$$

Forward converter is the developed form of buck converters. It has different versions as with one switched types.

3.5 Power Factor Correction Stages

As we mentioned in section 3.2, AC-DC converters need extra circuitry to improve the power quality of the power converter. This extra stage is traditionally applied with a PFC stage or cell. This section covers the PFC solutions.

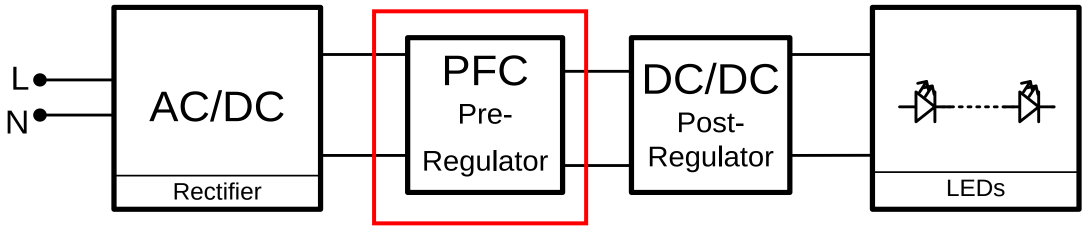


Figure 3.19 SMPS stages, PFC stage

3.5.2 Passive Power Factor Correction

Designers use passive elements and valley-fill diodes to achieve passive power factor correction like the converter in figure 3.20.

Passive PFC circuits pull current for more time in a cycle and improve the power factor of the converter. Passive PFC has an easy design and high efficiency about 96%. It has an unregulated output which causes a nonoptimized design for DC-DC stage. Also, it is not proper for both high and low line AC grid systems; a switch is used to select the voltage level. In some passive circuit designs, inductors are used which is unusually big in size.

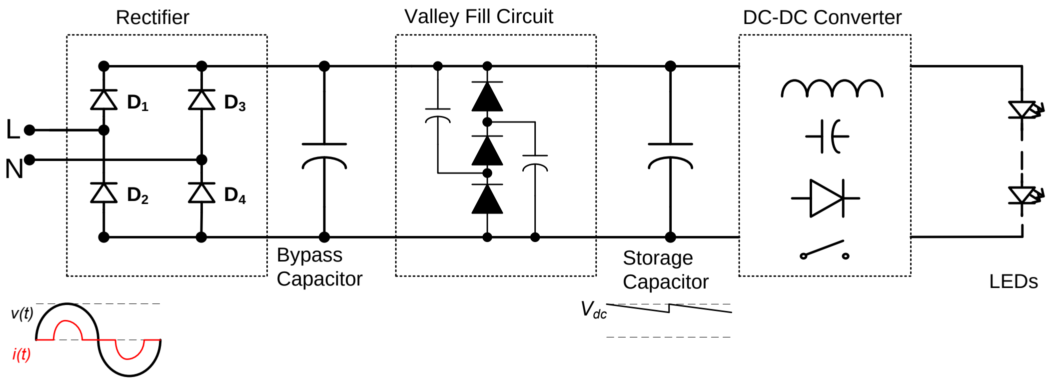


Figure 3.20 AC-DC SMPS with passive power factor correction

3.5.3 Active Power Factor Correction

Second method is active power factor correction; implemented with a pre-regulator circuit with active devices. Methods implemented for active PFC are; [16, pg95]

i. DC-DC rectifiers,
ii. PWM boost converter,
iii. Tapped transformer converters,
iv. Single-stage PFC AC-DC converters,
v. Vienna rectifiers,
vi. Other methods.

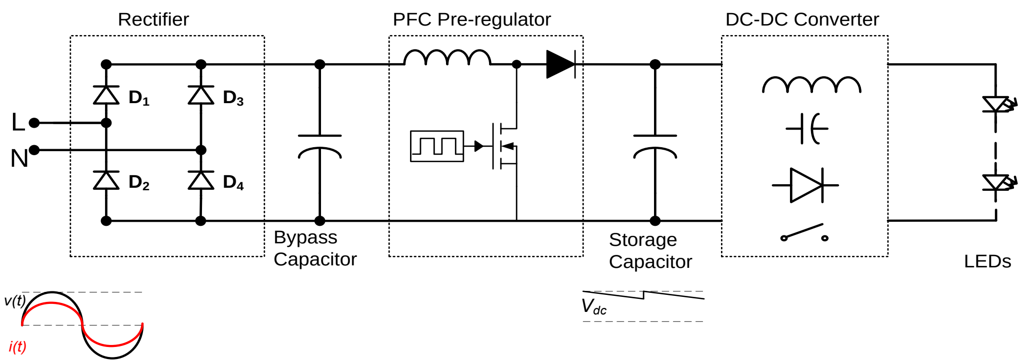


Figure 3.21 AC-DC SMPS with active power factor correction

Designers use a boost-converter for pre-regulator; boosting the input voltage to high level (400V generally). This pre-regulator follows the input voltage and tries to match the input current to this sinusoidal waveform by using an individual IC. This converter also reduces the phase difference between line voltage and current which means DPF=1. Figure 3.21 shows the active power correction stage of a power supply.

The figure 3.22 shows the pre-regulator circuit; a boost converter which has input as AC rectified line voltage. Converter circuit has to work between 0 V to peak value of AC line voltage and give output as a higher voltage (400 Vdc for high line input). Boost converter uses current mode control. Figure 3.23 illustrates the application of control by dividing the control system into parts. In this control the parameters are some real ones and some desired values. Here, i_s denotes the line input current and i_s* denotes the required input current. V_{dc} denotes the output voltage of the boost converter, V_{dc}* denotes the desired output voltage and v(t) denotes sinusoidal input voltage.

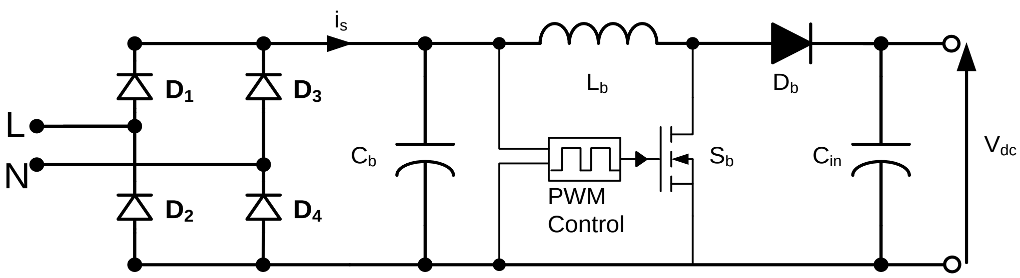


Figure 3.22 Pre-regulator boost converter power factor correction circuit

Control systems work with an error output voltage that is created with respect to the difference between the desired and measured voltages. The control block multiplies the input voltage by error voltage. Converter defines the position of the switch by comparing the waveform with respect to measured current value.

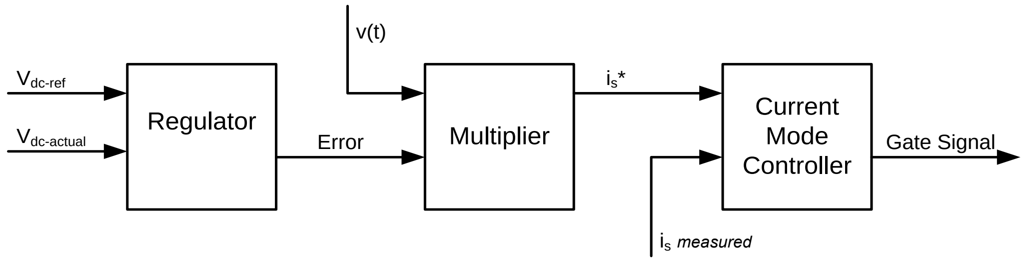


Figure 3.23 Boost converter control block diagram

The operation modes for PFC applications are; discontinuous conduction mode (DCM), continuous conduction mode (CCM) and critical or borderline conduction mode (BCM). Converter control mechanism defines these operation modes. There are several methods for these control mechanisms; current mode control; hysteretic control, constant-frequency control, constant-on time control, average current mode control. These control methods also defines the mode of the boost converter. These modes have advantages and disadvantages with respect each other.

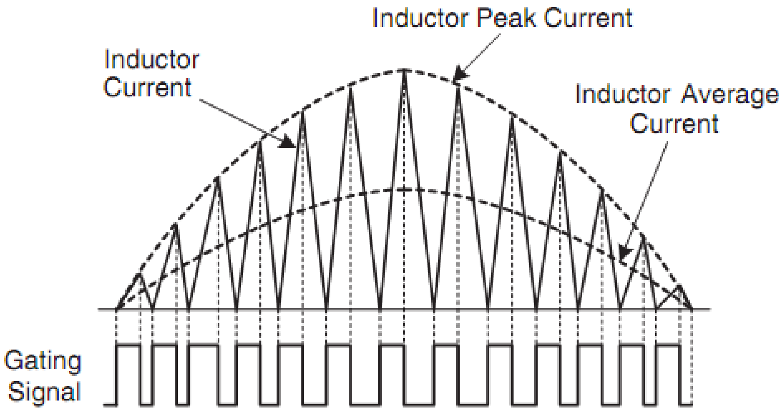


Figure 3.24 Boost inductor current waveform for BCM mode operation

Designers prefer DCM mode converters for the converters operating lower than 300 Watts. These converters have large size of inductor, which causes higher I^2R loss and loss due skin-effect. DCM mode guarantees that boost inductor cannot saturate because each switching cycle restarts after the current on inductor reaches zero. This application blocks the reverse-recovery losses and allows the designer to use cheaper diodes. The operation frequency changes with respect to on-time and switch moves to on position when current in the inductor is zero. Figure 3.24 shows inductor current and drive signal as gating signal at DCM mode of operation.

Designers prefer CCM mode operation for the powers higher than 300 Watts. The boost inductor current never reaches zero, decreasing I^2R losses and having lower ripple and smaller inductor packages. Designer has to design the working principle to ensure that inductor never saturates.

CCM operation is applied by average current control method which uses current mode control. Input current, which is boost inductor current; have to follow the voltage waveform. In the operation, there are two control loops as voltage and current control.

Designers prefer these types of power factor corrections stage as a pre-stage before the dc-dc converters in AC-DC power supply. This circuit configuration named as *"Two-stage power factor correction AC-DC power supply".* These converters achieve high power factor and high power quality with an extra circuit, which brings an extra cost, extra space and complex design issues. Designers prefer these converters for high power LED applications over 150 Watts.

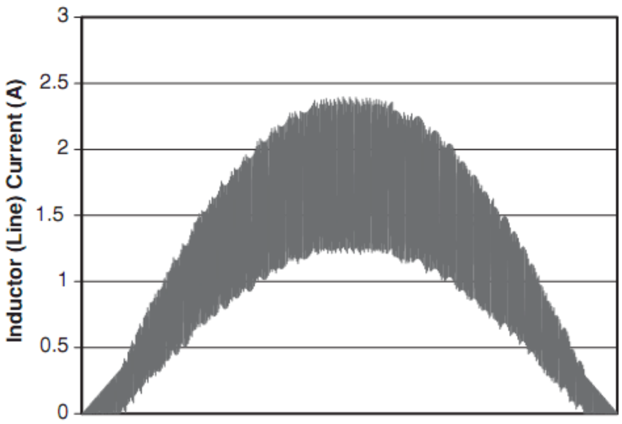


Figure 3.25 Inductor current waveform for CCM mode operation

3.5.4 Two-Stage AC-DC Converter for LED Driver

Two-stage power converters are expensive solutions for most of the LED applications; except high power applications. Standard street lighting applications with traditional light sources consume power about 400 W each. High power LED applications are in the range of 70 – 200 W, to solve the problems of outdoor high energy consumption problems and maintenance problems because of life-time. In other words, price is not the primary limitation for these applications.

Fairchild semiconductor introduces an application circuit for 70 W of high-power LED [19]. The figure 3.26 shows the layout of the proposed converter. In the figure first stage is *BCM Boost PFC*, which means border-line conduction mode Boost PFC as front-end PFC stage and second stage is Quasi-Resonant Flyback; the DC-DC part of the converter for back-end. The converter is a fifth generation SMPS with remarkable switching techniques applied to standard converter topologies.

This converter involves two active converters with two ICs. FL6961 is used for PFC stage; which guarantees BCM operation. BCM operation has advantages over CCM mode with better efficiency, no-loss for reverse recovery of boost diode and zero-voltage switching decreasing the losses. Other IC FL6300A; is a Quasi-Resonant (QR) Flyback converter IC, which guarantees to reduce switching losses with this switching technique also called as (valley switching) and increasing light-load efficiency with exceptional internal structure.

Researchers improved these converters by integrating the PFC stage into the dc-dc converter stage and saving from space, price and design with suffering some disadvantages. These converters are called *"Single-stage power factor correction AC-DC power supplies"*. Next section includes the history and development of single-stage converters.

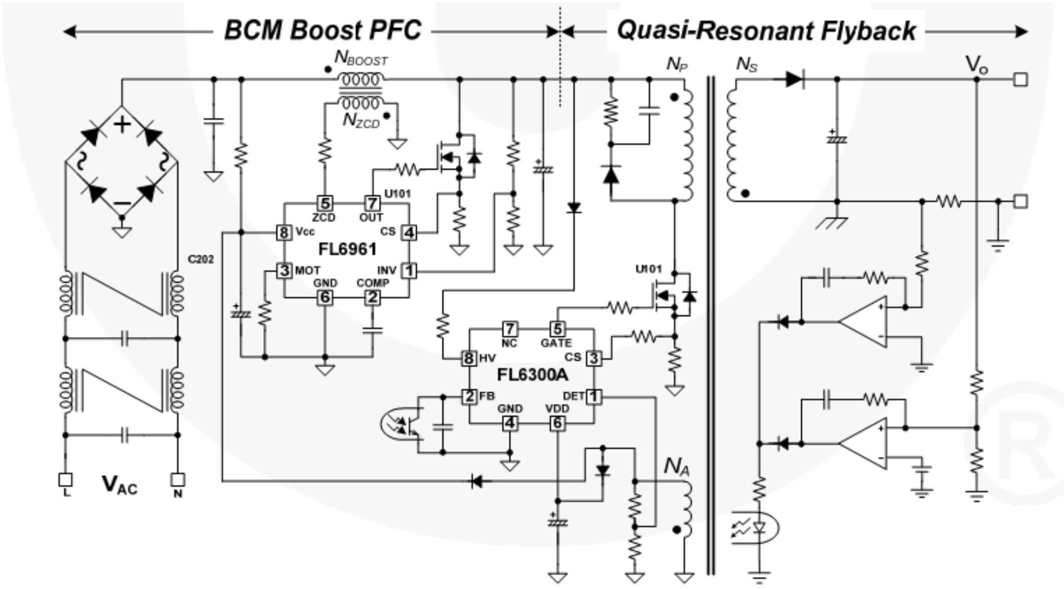


Figure 3.26 Two-stage PFC AC-DC LED driver [19]

3.6 Single-stage Power Factor Correction AC/DC LED drivers

3.6.1 Introduction

Single-stage PFC converters are the merged form of two-stage PFC converter to a single stage with a single switch. Two-stage converters have superior performance including complexity in their working system. They include two controlled system together, which decreases the efficiency. Single-stage converters shown in figure 3.27 have higher efficiencies and simpler design with respect to two stage power supplies. Main reason for preferring these devices is the cost-effectiveness and the smaller size; which is extremely serious issue for led driver for mid and low power application.

In single-stage converters; rectified AC line voltage is the input voltage of the DC-DC converter stage. Here, DC-DC converter stage implements both PFC function and DC-DC conversion with individual switching technique. Another difference from two-stage and usual AC-DC converters is the storage capacitor value is remarkably low. Capacitance value is less than 1 uF, so input of DC-DC converter is not constant. Here, the capacitance value has importance; has to provide low impedance for DC input and have to be small enough to offer high impedance to the AC line frequency.

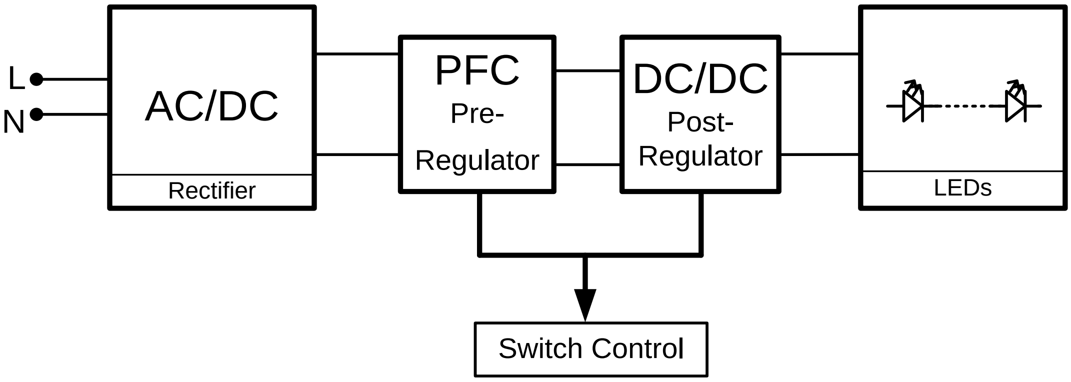


Figure 3.27 Single-stage PFC AC-DC power supply

3.6.2 Review of Single Stage Power Factor Correction Power Supplies

Single stage ac-dc power supplies researched since 1990s. Researchers developed several topologies and different systematic solutions in order to combine the two stages of PFC and DC-DC converters. Manufacturers produced individual ICs with the title of single-stage developed for several fundamental topologies. This section begins with the introduction of some of the first developed single-stage converters without giving the order of inventions. In the next section several developed topologies and the resultant circuits will be examined. Final part involves the recent developments of single stage converters.

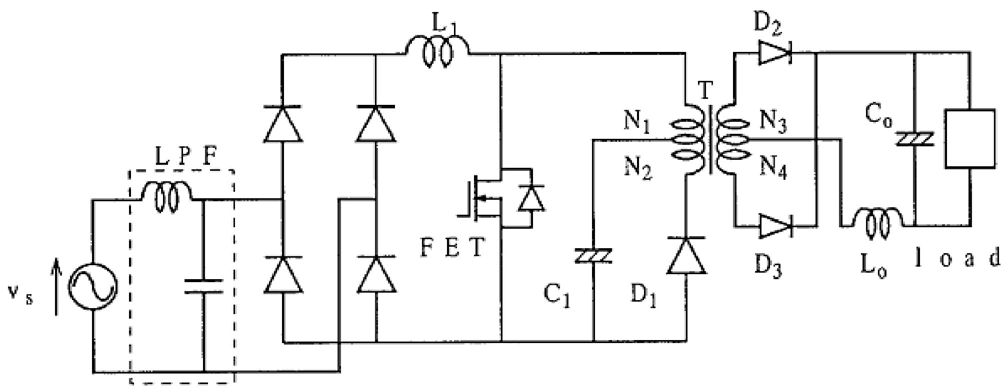


Figure 3.28 High power factor *dither* converter [20]

I. Akashi and R. Igarashi published a well-known circuit as *dither* in 1990 [20] shown in figure 3.28. Researchers demonstrate high power factor of 0.98 by a single switch control. This innovation uses a different control mechanism. In dither converter; researchers tried to convert the non-linear input voltage and input current relation of the conventional SMPS to a linear relation. Conventional rectifiers have peaky input current because input current flows at the time that input voltage exceeds the value of the storage capacitor as shown in figure 3.29, left part.

Solution for this problem is using inductor filter or resonant filter before the rectifier stage [20]. These improvements improve the PF value from 0.70 to 0.80 and decrease the harmonics with about 50%. However, this solution involves large inductors, which increase the size and cost of the converters.

Dither converters linearize, the non-linear characteristic of rectifier by using a voltage called dither. Dither voltage is a high-frequency voltage signal and equal to the storage capacitors voltage, E_d. Converter internal structure adds a dither voltage to the supply voltage, and the new formed rectifier pulls current more than one time.

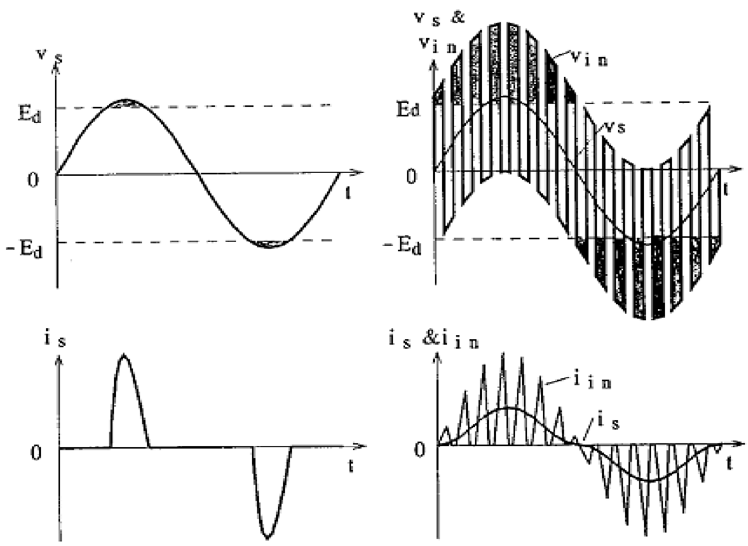


Figure 3.29 Conventional and dither rectifiers, input voltage and current waveforms

Figure 3.29 shows the input voltage and input current waveforms of conventional rectifier in left and dither rectifier in the right part of the graph. The average of resultant input current waveform; a quasi-sinusoidal waveform is obtained, and PF is improved up to 0.992, THD is 8.6% and efficiency is 78.9%.

In the same time researchers introduce a new family of single stage power supplies with the name of SSIPP or S^2IP^2 [21]. Researchers introduce a methodology in order to combine the PFC cell and DC-DC converter stage in to one stage. This methodology states that by using the dc-dc converter's switch and adding one or two diodes to the circuit and changing the layout; any PFC cell can be combined with DC-DC converter stage. In order to accomplish unity power factor, researchers suggest DCM mode of operation for both parts which eliminates the greatest drawback of single-stage converters with the fast regulation problems. Also, the voltage across storage capacitor becomes a function of load current, which changes the duty cycle with respect to load. In this converter energy balance is obtained by varying this voltage on storage capacitor; when there is low load energy imbalance is corrected with decreasing the duty cycle and increasing the storage capacitors voltage. DCM mode of operation also ensures energy balance but introduce drawbacks of DCM operation. These applications can reach PF value of 0.983. Researchers proposed several single stage converters after these converters. The survey [22] over these various types of converters showed the relationship between the converters. Many of the proposed topologies are electrically same with each other.

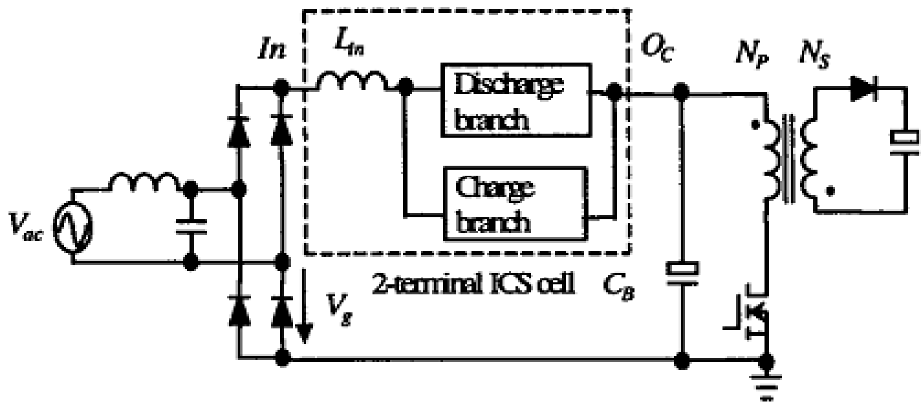


Figure 3.30 Two terminal input-current shaping-cell as pre-regulator of power converter

Here, all of the converters have an input current shaping cell, ICS. These converters can be divided into two sections; two-terminal ICS and three-terminal ICS shown in figure 3.30 and figure 3.31. Researchers work to generalize the ICS based converters [23]. Researchers developed new S^2IP^2 are converters during generalization.

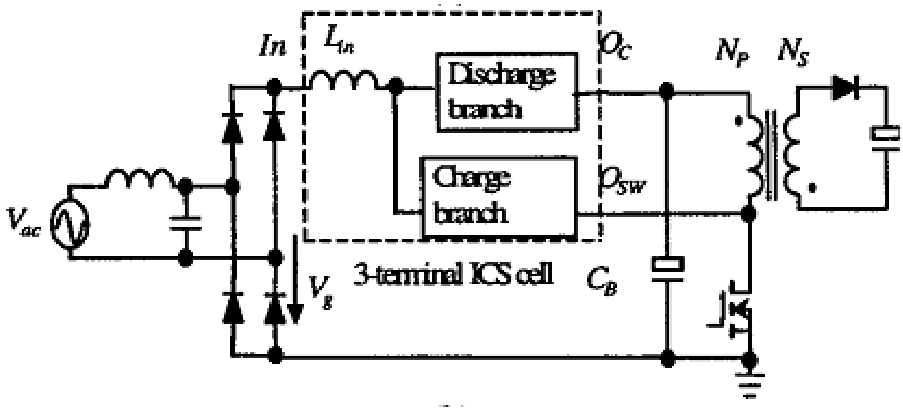


Figure 3.31 Three terminal input-current shaping-cell as a pre-regulator of power converter [23]

Another research introduced a different converter as Integrated High Quality Rectifier-Regulators (IHQRR). These converters can be based on flyback, buck or other dc-dc converters by [24]. Figure 3.32 shows the block diagram of the converter. The innovation of this converter is due to exact recognition of the operation principle of single-stage converters. The theory states that input dc voltage v_g, storage capacitor voltage v_c and the load voltage v, have to be independent of each other.

Also, the converters have to allow these voltages to vary arbitrarily. This operation is fulfilled with two ways. First researchers put impedances between these voltage stages. Second way is to insert switching elements between these elements. Researchers prefer switch and diodes for implementation. The independence of these voltages gives the ability to converter to provide a matched input current with input voltage waveform.

Well-known converter is investigated with applying this theory. Researchers name the converter as *Boost Integrated with Flyback Rectifier/Energy Storage/DC-DC converter (BIFRED).* Here, the boost stage stands for input current wave shaping and flyback converter stands for dc-dc converter regulating the output. The rule is to operate the stages in DCM mode. Another model is provided as *Boost Integrated with Buck Rectifier/Energy Storage/DC-DC converter (BIBRED).*

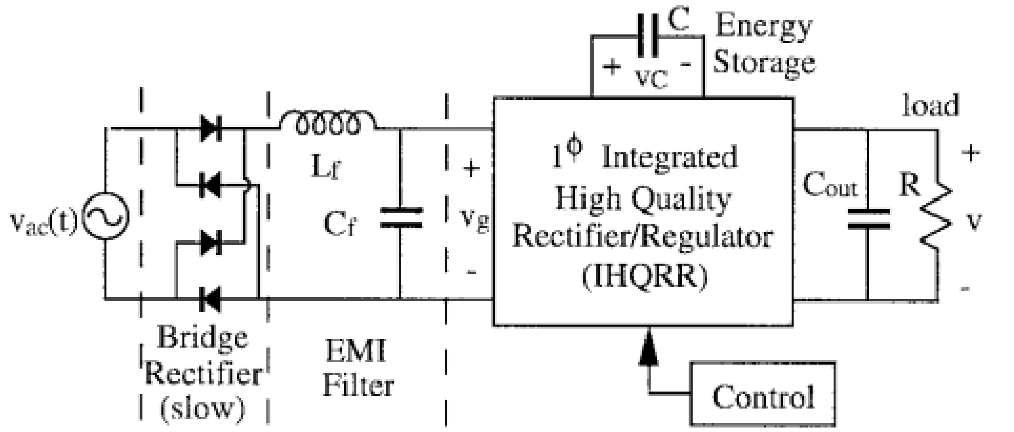


Figure 3.32 Schematic of integrated high quality rectifier-regulators [24]

Further works are performed to remove the energy balance problem and voltage stress [25] problem of single stage converters. Researchers explain the different ways; by changing the topological structure, using passive elements, and using developed ICs.

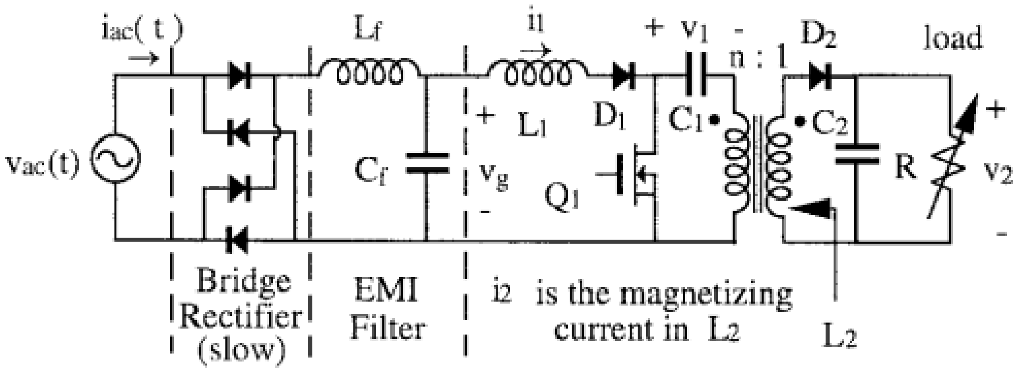


Figure 3.33 BIFRED, Boost integrated with Flyback/Energy storage/DC-DC Converter

3.6.3 Single Stage PFC Power Supplies Drawbacks and Solutions

Single stage converters are low cost, small size and efficient devices. However, it has some drawbacks with respect to operation mechanism and topologies. The researches and improvements on technology solved most of the problems since the investigation of various types of single stage converters in 1990s. This section covers all of the drawbacks with the solutions.

Converters have a large low-frequency ripple at the output stages. This phenomenon is a theoretical result all single stage converters have large ripple at 100 Hz. Also, output regulation of output voltage is slow. Most of the circuits are complex in the manner of circuit topology, circuit operation and converter control mechanism. Control loop for current control has a band-with of 10 to 30 Hz. So it cannot regulate the ripples on the line; so these ripples can be directly seen in the output voltage. For the solution, large capacitances should be used to regulate these ripples. For LEDs, critical point is not to violate the maximum current rating of LEDs.

The input voltage of DC-DC converter stage is designed to be variable, so there is no bulk capacitor for constant voltage. Energy is stored only in output capacitors and in the transformer; so there is no hold-up time for SMPS when it is unplugged, or energy is lost.

PF value decreases with increasing voltage or decreasing the load. This effect is due to the transfer function of the converter and non-linearity of the converter. Still the PF has value of 0.9 in the worst condition.

However, single-stage PFC converter circuits still have advantages of cost and size, which is a preliminary choice for LED applications for low and mid power range.

3.7 Three Special PFC AC/DC LED Drivers

In the literature survey, the developed types of single stage PFC converters for LED drivers are searched. Three types of applications are selected to be investigated deeply. In the survey three special SSPS are selected with respect to some constraints. First of all of the converters filtered for LED applications. Second constraint of the selection is low component and low cost designs. Last constraint is easy design and high performance converters. Filtering the surveys with respect to these constraints, three special SSPS application are selected. First single stage converter is a developed flyback converter. The developments with respect to standard flyback are new circuit elements and re-arranged transformer. Converter uses an individual IC for correct operation mode. Second one is a SEPIC converter with single stage application. This converter uses standard SEPIC topology with an individual IC. Last circuit is a single-stage flyback converter which is a commercial product for LEDs.

3.7.1 Single-Stage Flyback Power-Factor-Correction Front-End for HB LED Application [26]

The proposed converter is a modified version of conventional flyback converter. Extra components of the converter are; an individual transformer, a boost inductor and a PWM controller (NCP1207). This patented invention [27] comes from integration of PFC stage with DC-DC stage.

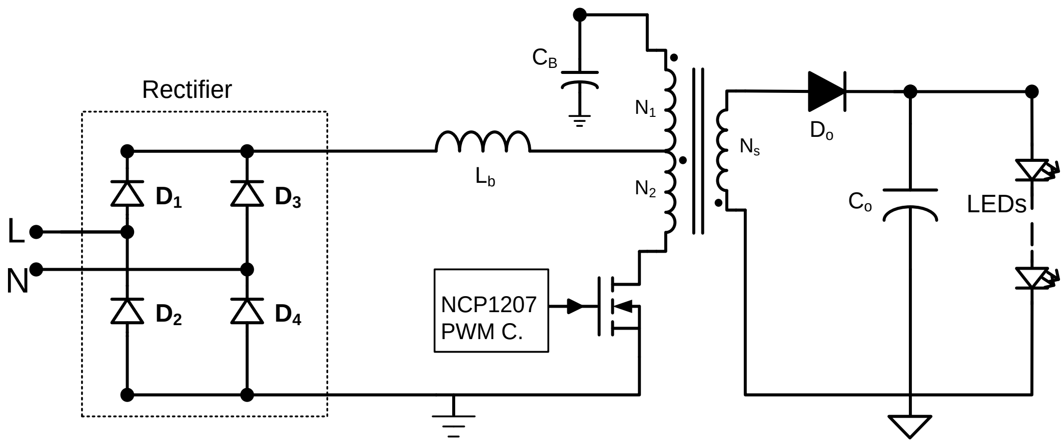


Figure 3.34 Single stage Flyback AC-DC converter for LED driver [25]

Researchers propose the converter operation mechanism and a prototype of the converter for unique LED application. The standard design cannot be applied to universal input range; so researchers developed the optimization of the circuit elements in order to work with low line

(90-140 Vac) and high line input (180-275 Vac). Researchers include further work for improvement of universal input applications in [28]. Researchers developed the prototype of the converter and detailed the circuit passive elements values. They practiced the prototype for different load conditions, different input voltage levels and different circuit components. Converter has an output voltage of 24 V and current of 3.25 A. In order to test; the output is Philips Lumileds LXHX-LW3C LEDs in strings of seven series within four parallel branches. Converter reaches maximum 0.98 PF for low line and 0.95 PF for high line and minimum PF values can go down to 0.9. The efficiency of the converter changes 85% to 90%.

3.7.2 Design Considerations of High Power Factor SEPIC Converter for High Brightness White LED Lighting Applications [29]

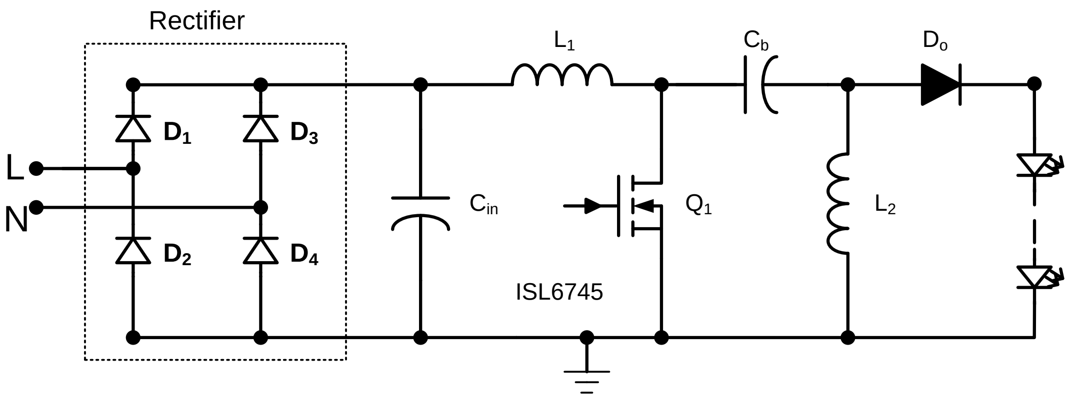


Figure 3.35 SEPIC AC-DC converter for LED applications [29]

Proposed converter provides a high-power factor with single stage ac-dc converter by using standard Single-Ended-Primary-Inductance-Converter (SEPIC) topology. Converter uses an individual IC; ISL6745 for the PWM controller. Converter operates in DCM mode and control system includes both voltage and current control. Application circuit also ensures dimming option just by changing the value of a potentiometer.

Design parameters for both power stage and control stage are critical for correct operation. Converter does not need to sense the input voltage waveform to shape the input current; IC implements current shaping automatically.

Designers introduce a prototype of the proposed converter for wide input voltage range. Output of the converter is twenty-one HBLEDs connected serially. Designers give all of the converter circuit elements properties except the control parameters. LEDs drive current increases up to 400 mA and full-load output power of the converter is 28 Watts. Prototype converter operated in different input voltage levels and different output loads. Converter works with PF value of 0.9 in the worst condition. As the output load increases, PF value also increases maximum to 0.995.

This single-stage power supply does not use any element as PFC cell, DC-DC converter operates for wide input. Single switch control ensures power factor operation.

3.7.3 Single Stage Flyback LED Driver: RECOM RACD - 30-700

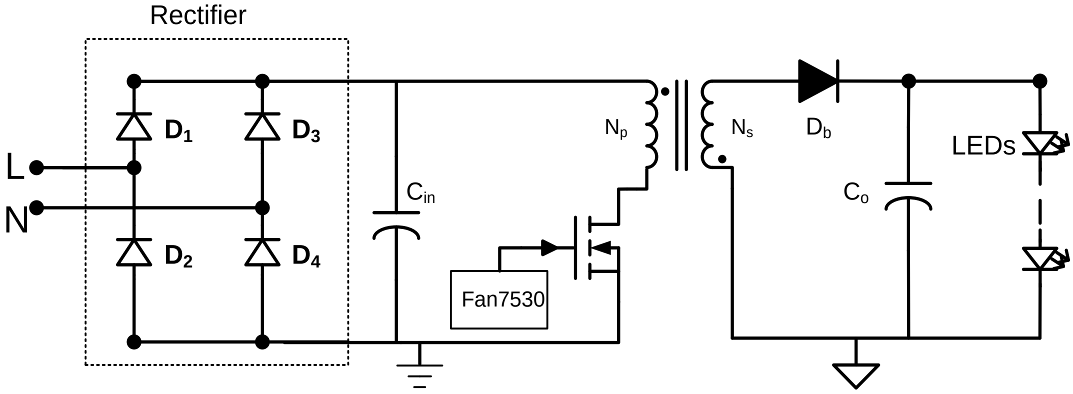


Figure 3.36 Single-stage AC-DC flyback LED driver

Final single-stage power supply is a RACD-30-700 which is a commercial power supply form the market. This converter includes standard ac-dc rectifier and dc-dc stage is a flyback converter. Additionally this product has an extra dc-dc buck stage at the output of the flyback converter.

This converter has an output power of 30 Watts and 700 mA of output current. The converter can go up to 0.95 PF value. Similarly to other converters as the input voltage decreases PF value increases and also as the output load increases PF value increases.

CHAPTER 4

DESIGN AND IMPLAMENTATION OF SINGLE STAGE HIGH POWER FACTOR SEPIC CONVERTER FOR LED APPLICATIONS

4.1 Review of SEPIC topology

SEPIC converter is a dc-dc converter with property of both step-down and step-up with positive output. SEPIC name is the abbreviation of single-ended primary-inductor converter. The prominence of this converter is working like buck-boost converter with a positive output voltage. Figure 4.1 shows the basic layout of SEPIC topology.

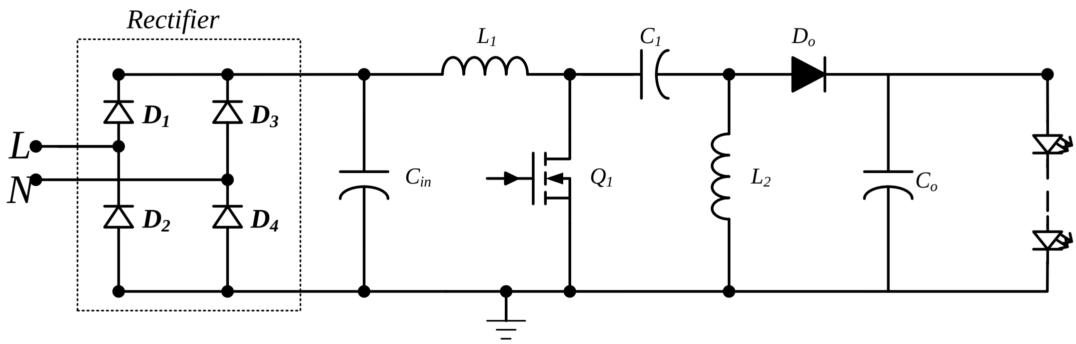


Figure 4.1 Single-stage high power factor SEPIC converter [29]

This chapter introduces the single-stage SEPIC converter with high power factor. First section covers analyze of SEPIC converter as a dc-dc converter. This analyze involve operation principle of the converter. Next section involves the proposed single-stage SEPIC converter in research [29]. These steps detail every component of the converter; passive and active. Next part is the computer simulations of proposed converter. Computer simulations involve the application of the converter active elements and performance analysis in ideal conditions. Final part details the experimental circuit with its application and performance analysis.

This section covers SEPIC dc-dc operation mechanism within two modes of operation. The analysis includes the function of the components and voltage transfer ratio. Next section describes the switch model from Vorperian's [30] model. Figure 4.2 shows the SEPIC converter circuit diagram.

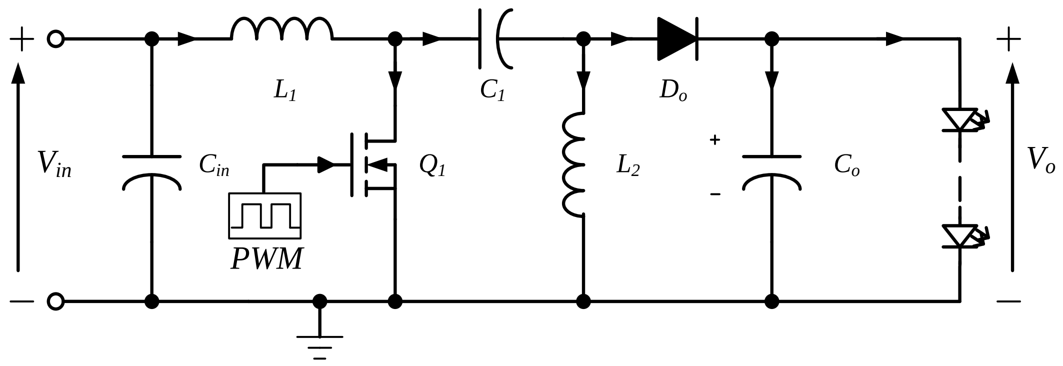


Figure 4.2 DC-DC SEPIC converter basic layout

Circuit operation can be divided in to two modes with respect to the position of the switch. Figure 4.3 and Figure 4.4 shows the circuit layout with respect to different positions of the switch. When the switch (Q_1) switched on, output diode (D_o) is reverse-biased. The primary inductor (L_1) starts to charge, secondary inductor (L_2) and ac coupling capacitor (C_1) forms a resonance circuit. Here, load pulls current from the output capacitor (C_o).

During this state, input capacitor (C_{in}) voltage and L_1's voltage is equal to input voltage (V_{in}). Also C_1's voltage and L_2's voltage are equal to V_{in} in this operation mode. Voltage on the C_1 can be calculated easily by the next stage with KVL.

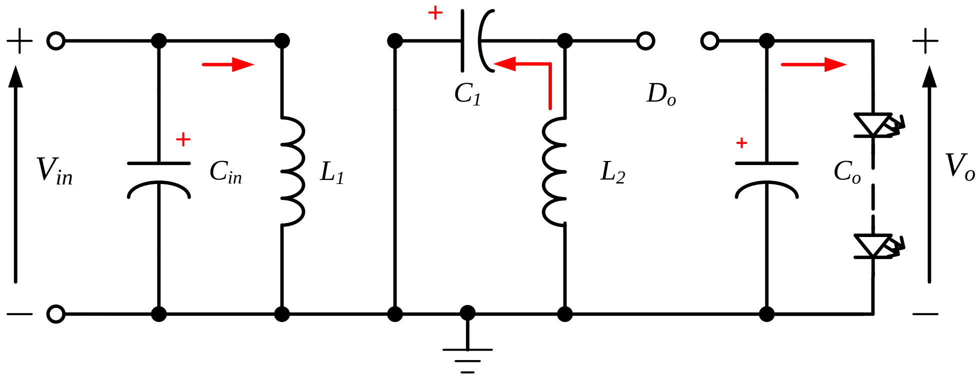


Figure 4.3 SEPIC converter mode 1: switch on, diode off

In the second mode, the switch is off, and diode is forward biased. C_{in}, L_1, C_1, L_2 form a loop. Here, the voltage values of the capacitors are steady, and the inductor voltages change. Inductors current decreases which means the stored energy of inductors releases in this mode. The load is directly connected to the inductors.

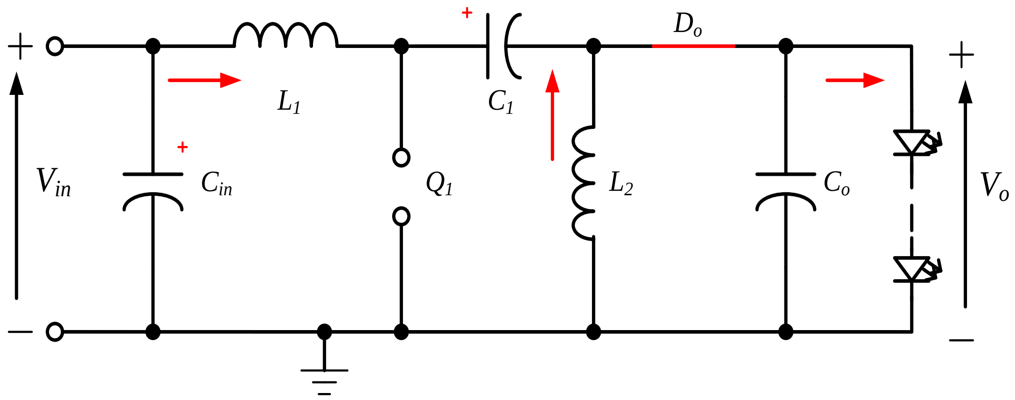


Figure 4.4 SEPIC converter mode 2: switch off, diode on

4.1.1 DC Analysis of SEPIC converter

The voltage transfer ratio can be directly calculated by analyzing the voltages over the inductors for steady state conditions. However, Vorperian's PWM switch eases the calculation of the voltage transfer ratio.

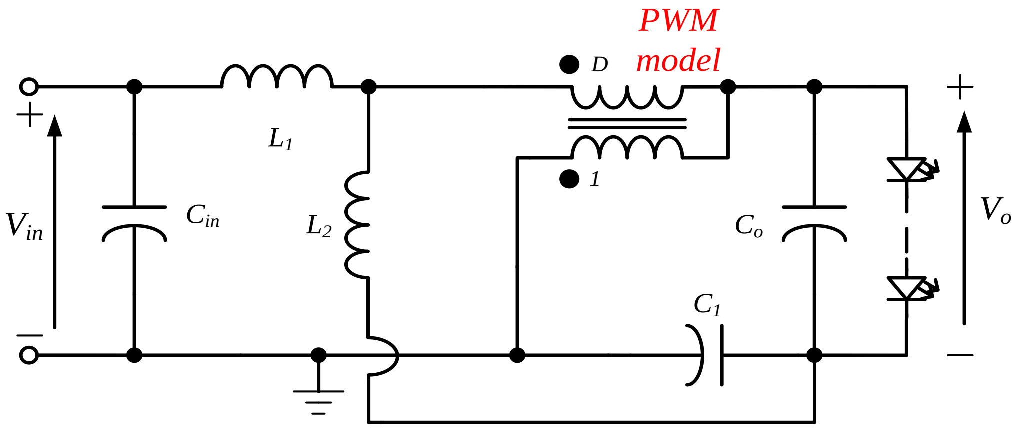


Figure 4.5 SEPIC converter integrated PWM model

This part introduces the PWM switch model. [31] Figure 4.5 shows the integrated PWM switch model of SEPIC converter and figure 4.6 introduces the simplified version for DC analysis. For DC analysis, inductors are changed with short circuits and capacitors are changed with open-circuits. This simplification neglects the parasitic of the converter.

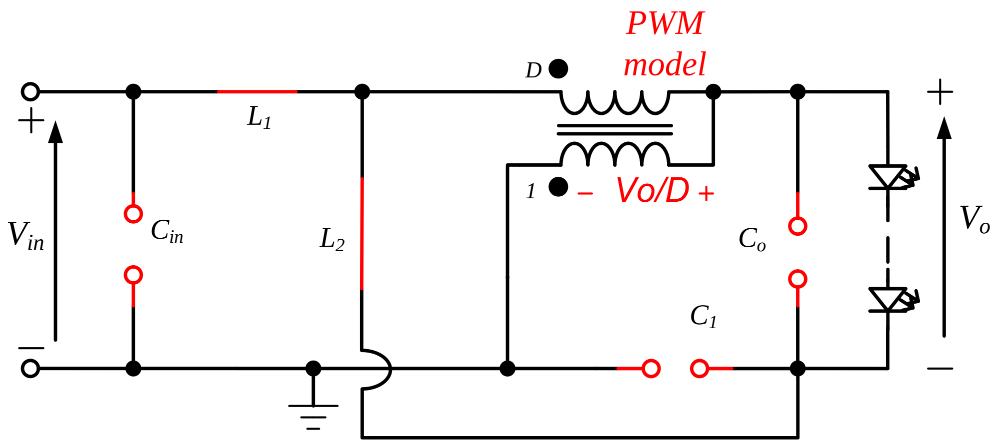


Figure 4.6 SEPIC converter DC model

In order to obtain the relationship between input voltage (V_{in}) and output voltage (V_o); KVL is applied to the simplified version of SEPIC converter. Equation 4.1 introduces the loop equation and equation 4.2 shows the voltage transfer ratio. In the equation duty cycle of the gate signal is defined with D.

$$V_{in} - V_o \;\; D + V_o = 0 \tag{4.1}$$

$$\frac{V_o}{V_{in}} = \frac{D}{1-D} \tag{4.2}$$

4.2 Single-stage High Power Factor AC-DC SEPIC LED Driver

4.2.1 Introduction

This chapter introduces the proposed converter circuit of single-stage SEPIC LED driver. First part begins with the details of basic operation principle and modes of operation. Next section is the parameter list and the calculation of proposed converters component parameters. Final part includes the resultant waveforms and performance of the converter. Proposed AC-DC driver has two parts as usual; first part is AC-DC rectifier which is a full-bridge rectifier converters AC voltage to DC just inverting the negative part of the input waveform.

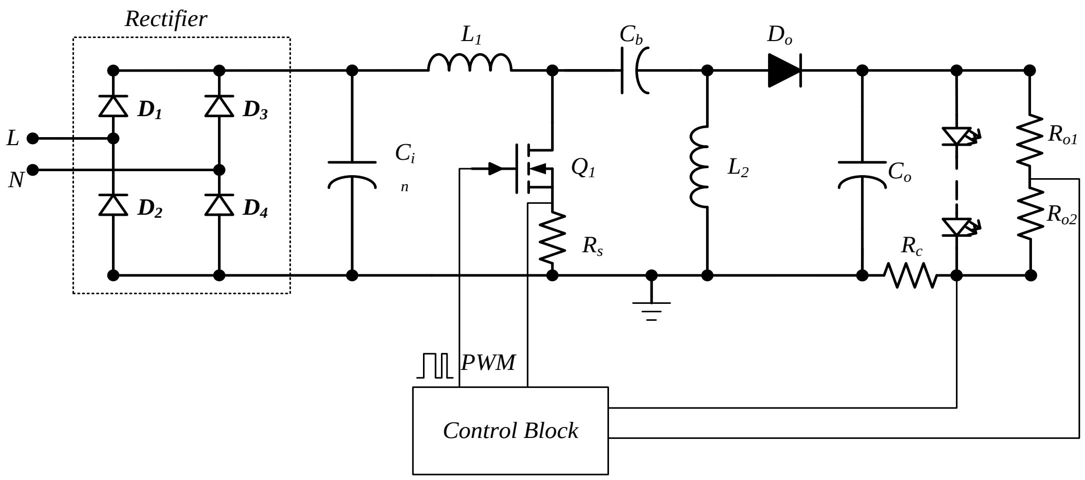


Figure 4.7 Single-stage high power factor AC-DC SEPIC converter

Second part is DC-DC converter, a SEPIC converter as usual. Fundamental elements of SEPIC converter are input capacitor (C_{in}), primary inductor (L_1), secondary inductor (L_2), SEPIC capacitor (C_b) output diode (D_o), output capacitor (C_o), and switch (Q_1). Control block consist PWM controller and feedback control circuit; the control elements are switch current sense resistor (R_s), LED current sense resistor (R_c) and output voltage sense resistors (R_{o1}), (R_{o2}). Differently, C_{in} is not a storage capacitor as in traditional SMPSs; it is a small capacitor that the voltage on it is similar to line voltage.

Converter works in DCM mode of operation and controller has signal inputs; switch current, output voltage by current divider and output current by a current sense resistor connected serially to LEDs. Controller provides over current protection by controlling switch current and over-voltage protection by sensing the output voltage. Converter has dimming function, which uses a potentiometer to change the sense voltage over sense resistor. The converter operation mechanism has three modes; first is switch on-diode off, second is switch off-diode on, finally switch off-diode off.

4.2.2 Converter Operation Mechanism

Converter input voltage (v_{in}) is the sinusoidal line voltage which is formed as a sinusoidal voltage with angular frequency (ω) and amplitude (V_l);

$$v_{in} = V_l \sin(\omega t) \tag{4.3}$$

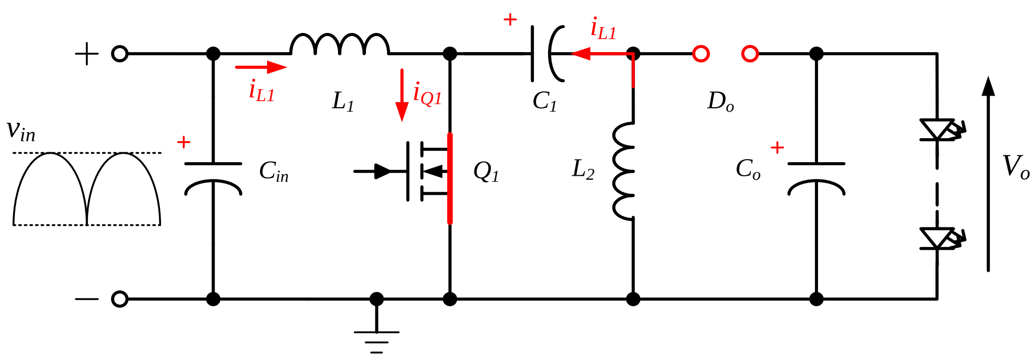


Figure 4.8 AC-DC converter mode 1: switch on, diode off

First mode of operation starts when the switch is on, and diode is off. Figure 4.8 shows the form of the converter in this mode. The time period of this mode is defined as on time period (T_{on}) in one switching period (T_s). This period is also defined as duty cycle (D) of the gate signal.

$$T_{on} = DT_s \tag{4.1}$$

L_1 has the same voltage with C_{in} and voltage across the capacitor C_1 is equal to the input voltage (from steady state equations, shown in the previous section) which means the same voltage is on the inductor L_2. Input voltage is constant during switching period, because the period of input voltage is much lower than switching period. Also, the switch current (i_Q) is the total of primary inductor current (i_{L1}) and secondary inductor currents (i_{L2}). Following equations show these current values, in the equation initial value of inductor current are denoted with $i_{L1}(0)$.

$$i_{L1}(t) = i_{L1}(0) + \frac{v_{in}}{L_1}t \tag{4.2}$$

$$i_{L2}(t) = -i_{L1}(0) + \frac{v_{in}}{L_2}t \tag{4.3}$$

$$i_Q\ \ t\ \ = i_{L1}(t) + i_{L2}(t) = \ \frac{v_{in}}{L_1} + \frac{v_{in}}{L_2}\ \ \ t \tag{4.4}$$

Inductors store energy in this mode and inductor currents have initial values at each switching period. Their current increases linearly with respect to voltage across them in each switching cycle. The switching frequency is constant during the operation. Controller defines the on time period, which is the ratio of input and output voltage, which is:

$$\frac{V_o}{V_{in}} = \frac{D}{1-D} \tag{4.5}$$

Second mode of operation starts with the end of the on time period; switch is off and diode is forward biased directly. Figure 4.9 illustrates the active device conditions and circuit layout.

By writing the KVL equations for loops of the circuit, it shows that voltage on inductor L_2 is $-V_o$ and voltage on L_1 is equal to V_o.

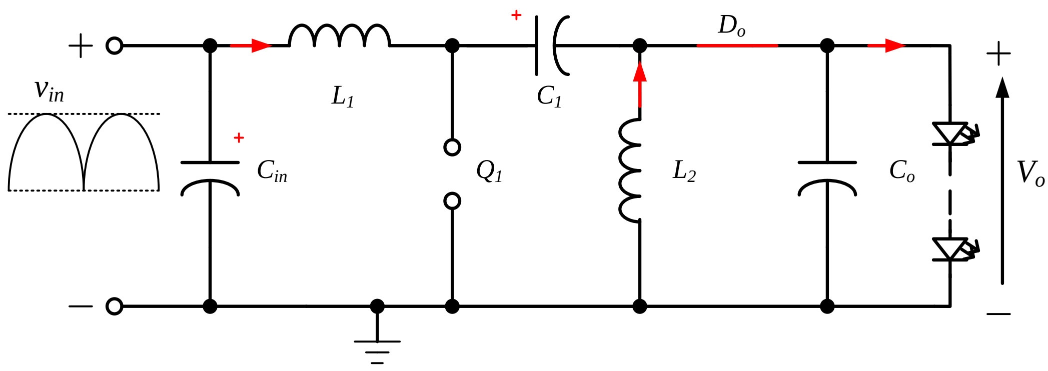


Figure 4.9 SEPIC converter mode 2: switch off, diode off

$$i_{L1}\ t\ = i_{L1}\ 0\ + \frac{v_{in} DT_S}{L1} - \frac{V_o}{L_1} t \tag{4.6}$$

$$i_{L2}\ t\ = -i_{L1}\ 0\ + \frac{v_{in} DT_S}{L2} - \frac{V_o}{L_2} t \tag{4.7}$$

$$i_{Do}\ t\ = \ \frac{v_{in}}{L1} + \frac{v_{in}}{L2}\ \ T_{on} - \ \ \frac{v_{in}}{L1} + \frac{v_{in}}{L2}\ \ V_o t \tag{4.8}$$

At the end of this mode, the current values of inductor L_1 and inductor L_2 are equal, but just the opposite because of polarity and the direction of current waveforms. In the equations, the initial current values, i_{L1} (0), and i_{L2} (0) values are equal and the total of two inductors current is equal to current of output diode (i_{Do}). The equation 4.12 shows the off time of switch (T_{off}) in a switching time period. In the equation 4.12 and 4.13, transfer ratio is shown with M.

$$T_{off} = DT_S \frac{v_{in}}{V_o} = \frac{DT_S}{M} \sin \omega t \tag{4.9}$$

$$M = \frac{V_o}{V_l} \tag{4.10}$$

Third mode of operation is the dead time operation; both switch and diode are in off position.

In this mode, the current values of inductors are constant and same. They have reverse polarity as mentioned in the previous mode. The current values can be calculated with rearrangement of the equations 4.7 and 4.11. Also, the dead time of the operation have to be defined in order to guarantee this mode, which ensures the converter operates in DCM mode.

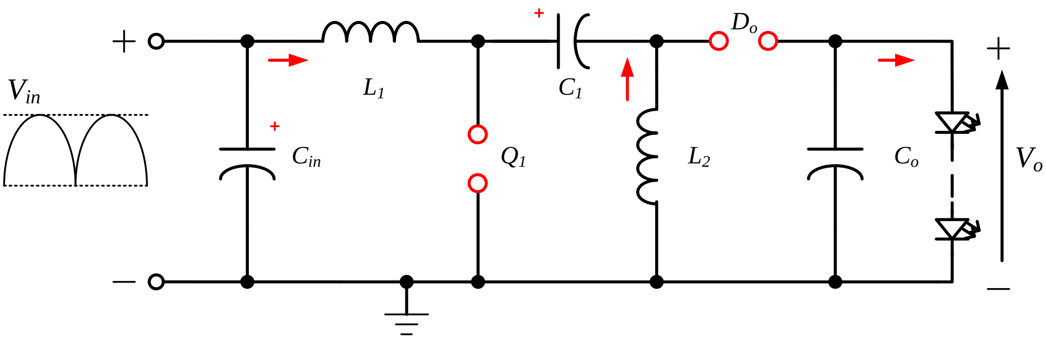


Figure 4.10 AC-DC converter third mode: switch off and diode off

The equations 4.14 and 4.15, shows the inductor current waveforms. Here the voltage on C_1 is shown with v_{c1}, it is also equal to v_{in}.

$$i_{L1}(t) = i_{L1}(0) + \frac{V_{c1} D T_s}{L1} - \frac{V_o}{L_1}(1-D)T_s \tag{4.11}$$

$$i_{L2}(t) = -i_{L2}(0) + \frac{v_{c1} D T_s}{L2} - \frac{V_o}{L_1}(1-D)T_s \tag{4.12}$$

Time interval for this mode is defined as dead-time (T_d) which equation 4.16 shows;

$$T_d = T_s - T_{on} - T_{off} \tag{4.13}$$

Controller has to provide the following conditions for DCM mode of operation.

$$T_s > T_{on} + T_{off} \tag{4.14}$$

$$D > \frac{V_o}{V_{in} + V_o} \tag{4.15}$$

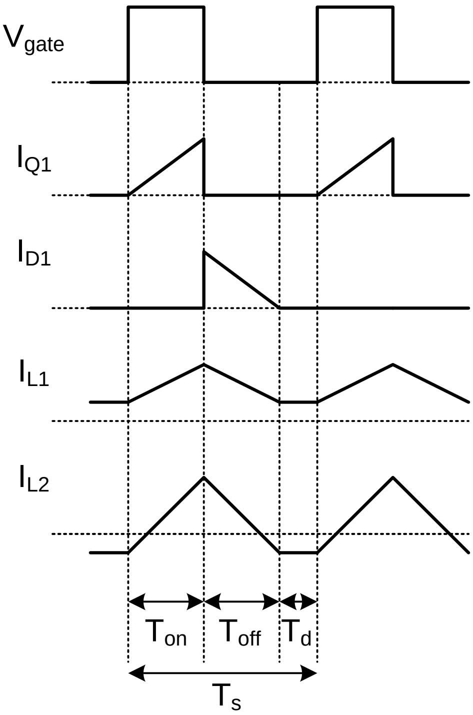


Figure 4.11 Switching waveforms for one switching period

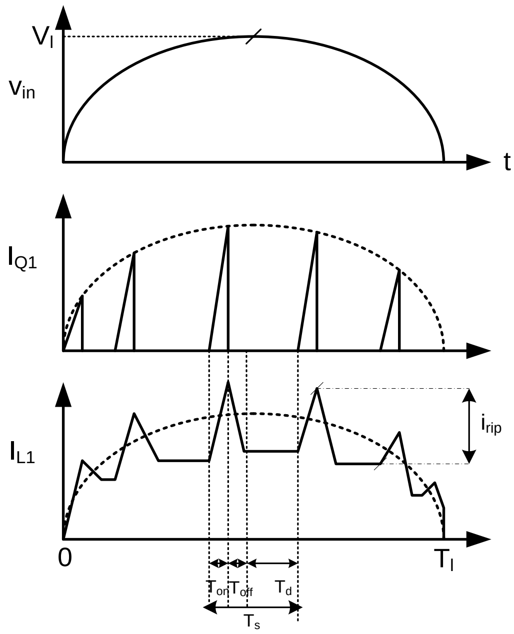


Figure 4.12 Switching waveforms for one cycle offline period

Figure 4.11 shows the characteristic waveforms for a switching period and the figure 4.12 shows the waveforms of inductor's L1 current, switch current and input voltage for half line period. These figures just illustrate the waveform with respect the principle of operation and not the exact waveforms. Input line current is the average of the current of output diode for half of line period. During this mode, diode is forward biased. Equation 4.19 shows the diode current (i_d) and equation 4.20 shows the output current (I_o).

$$i_d\ t\ = i_{L1}\ t\ + i_{L2}\ t\ = \frac{1}{L_1//L_2}\left(V_{c1}T_{on} - V_o t\right) \tag{4.16}$$

$$I_o\ t\ = \frac{1}{T_s}\int_0^{T_s} i_D(t)\,dt = \frac{1}{L_1//L_2}\,\frac{(T_{on}V_l\sin(\omega t))^2}{2T_sV_o} \tag{4.17}$$

The equation 4.21 shows the equality of input and output power assuming efficiency of 100%. In the equation i_{in} denotes input line current, v_o denotes output voltage and i_o denotes output current.

$$v_{in}\ t\ i_{in}\ t\ = v_o i_o \tag{4.18}$$

The equation 4.22 shows the average value of output current ($I_{o,avg}$), where T_l denotes the line period of AC mains.

$$I_{o,avg} = \frac{1}{T_l}\int_0^{T_l} I_o(t)dt = \frac{1}{L_1//L_2}\frac{d^2T_sV_l^2}{4V_o} \tag{4.19}$$

From these equations input line current can be calculated as shown in figure 4.22. In the equation I_l denotes the magnitude of input line current sinusoidal waveform.

$$i_{in}\ t\ = \frac{1}{L1//L2}\frac{v_{in}D^2T_s}{2} = I_l\sin(\omega t) \qquad I_l = \frac{1}{L_1//L_2}\frac{d^2T_sV_l}{2} \tag{4.20}$$

There is boundary between the DCM and CCM mode of operation. These values change with respect to the operation of standard dc-dc converter and dc-dc converter operating as a power factor controller.

4.3 Design of Single-Stage SEPIC AC/DC Converter

Previous section introduced the circuit voltage and current waveforms and time intervals. This part involves the converter working conditions and design parameters. First part initializes the converter input and output specifications. Next section follows with calculations of passive elements and confirming the operation conditions with selected components. Final section introduces the converter's active elements and converter's operation [32].

4.3.1 AC-DC SEPIC Converter Working Conditions

Proposed operation of the converter occurs with, special working conditions and proper design of circuit elements. This part includes the limit values of the elements, which guarantees the circuit operation principle.

The proposed converter has to work in the mode of discontinuous conduction mode (DCM). Section 4.2.3 defined the modes of the converter and the inequalities for DCM operation. As the condition, in 4.17 states the total of the on-time and off-time interval have to be shorter than switching cycle which brings following inequality using (4.12), (4.13), and (4.18);

$$D\ (1 + \frac{\sin \omega t}{M} < 1 \qquad (4.21)$$

The worst condition occurs at the peak value of the input voltage, which occurs at wt=90° which calculates to be;

$$D\ < \frac{M}{M+1} \qquad (4.22)$$

Another fact is the average output current ($I_{o,avg}$). Here, the load, LEDs, is just a resistor (R_L).

$$I_{o,avg} = \frac{V_o}{R_L} \qquad (4.23)$$

The equations 4.21 and 4.26 both give the value of $I_{o,avg}$ and introduce a conduction parameter (K_a), which is defined by research [33]. In the equation 4.28 L_{eq} denotes equivalent resistance of L_1 and L_2.

$$D = \ \overline{2}M \ \ \overline{K_a} \qquad (4.24)$$

$$K_a = \frac{2(L_1//L_2)}{R_l T_s} \quad , \ L_{eq} = L_1//L_2 = \frac{R_l T_s K_a}{2} \qquad (4.25)$$

DCM mode of operation brings conduction parameter's critical value ($K_{a,cri}$) for DCM mode [33] equation will be used;

$$K_{a,cri} = \frac{1}{2(1+M)^2} \tag{4.26}$$

The inductance value of L_1 can be defined from the ripple of the current (i_{rip}) flows through the inductor. Figure 4.12 shows this current ripple.

$$i_{rip} = \frac{v_{in} D T_s}{L_1} \tag{4.27}$$

The maximum current ripple occurs at the peak voltage input at $\omega t = 90°$,

$$i_{rip} = \frac{V_l D T_s}{L_1} \qquad : L_1 = \frac{V_l D T_s}{i_{rip}} \tag{4.28}$$

The value of the second inductor L_2 can be calculated by using (4.27) to (4.31)

$$L_2 = \frac{L_{eq} L_1}{L_1 - L_{eq}} = \frac{R_l T_s K_a V_l d T_s}{R_l T_s K_a I_{rip} - 2 V_l d T_s} \tag{4.29}$$

Another limitation has to be ruled for the capacitance value of the capacitor C_1. First consideration is the voltage of C_1 is assumed to be constant for one switching period. Second consideration is the capacitance value has to be arranged in a way that it has to be independent of the other storage elements. Therefore the input current can match the input voltage waveform.

First of all, the resonant frequency between C_1, L_1 and L_2 has to be greater than the line frequency in order to prevent the oscillations on the line current. Also, the resonant frequency between L_2 and C_1 must be lower than the switching frequency. This restriction provides that the voltage of the capacitor is constant during a switching cycle. The voltage values, of the input capacitor C_{in} and SEPIC capacitor C_1 have to be same. Otherwise, there is a possibility of inductors to move into CCM operation, which is the result of the change in the voltage of capacitor C_1. This operation causes the capacitor to be dependent to the circuit variables and risks the single-stage principles of operation. In the equation 4.33, ω_r denotes the angular resonant frequency and ω_s denotes angular switching frequency.

$$C_1 = \frac{1}{\omega_r^2(L_1+L_2)} \qquad \omega < \omega_r < \omega_s \tag{4.30}$$

Equation 4.33 shows the capacitance value of input capacitor of SEPIC converter [34]. In the equation K_{rpv} denotes voltage ripple factor on C_1, I_l denotes peak current value of input current.

$$C_{in} = \frac{4(i_{rip}/I_l)DT_sMI_o}{K_{rpv}V_lL_2} \tag{4.31}$$

Equation 4.33 shows the capacitance value of output capacitor of SEPIC converter; where $V_{rp\text{-}p}$ denotes the voltage ripple at C_o.

$$C_o > \frac{V_lI_l}{2V_{rp-p}V_o\omega_l} \tag{4.32}$$

4.3.2 AC-DC SEPIC Converter Specifications

This section covers converter specifications and the proposed features of the evaluation board will be introduced. [34] Converter operates at universal range input, and the load is twenty-one PLEDS operating with 350mA. Converter has to provide high-power factor, over-voltage and over-current protection and dimming opportunity. Table 4.1 details the converter specifications.

Table 4.1 AC-DC SEPIC converter specifications

Feature	Parameter
Input Line Voltage	85 Vac – 275 Vac
Input Line Frequency	50 – 60 Hz

Table 4.1 (continued)	
Input Current Ripple	20%
LED Load	21-series HB-LED
LED Voltage Range	63 ~ 73.5 V_{DC}
LED Current	0 – 300 mA
Converter Efficiency	> 75%
LED Current Ripple	<10%
LED Voltage Ripple	<5%
Power Factor	>0.95
Switching Frequency	150 kHz
Operation Mode	DCM
PWM Controller	ISL6745
Feedback Controller	EL5220

4.3.2.1 Step 1: Duty cycle calculation

The converter has to work for both high and low input voltages. The worst condition for the boundary mode of operation occurs at high voltage, so in the design we will use highest input AC voltage as from (4.3);

$$V_l = \sqrt{2} * 275 = 373 \text{ V} \tag{4.33}$$

Equation 4.36 shows the calculation of the parameter M by using the equation 4.13:

$$M = \frac{73.5}{373} = 0.1957 \ , \tag{4.34}$$

The parameter K_a is shown by equation 4.28. This parameter defines the boundary condition between CCM/DCM modes for SEPIC converter.

$$K_{a-crit-h} = 0.325, \tag{4.35}$$

The condition $K_a < K_{a\text{-crit}}$ provides DCM mode of operation. It is selected to be,

$$K_a = 0.3 \tag{4.36}$$

The equation 4.27 calculates the duty cycle;

$$D = 0.1516 \tag{4.37}$$

Figure 4.13 shows the change in the duty cycle with respect the change in the input voltage for half line period. The principle of the change in duty cycle is similar for the other half line cycle.

Selection of duty cycle value is for the highest input voltage. Therefore, this value is the minimum value of the duty cycle during the line period. Calculation of passive elements uses this value and guarantees the DCM mode of operation.

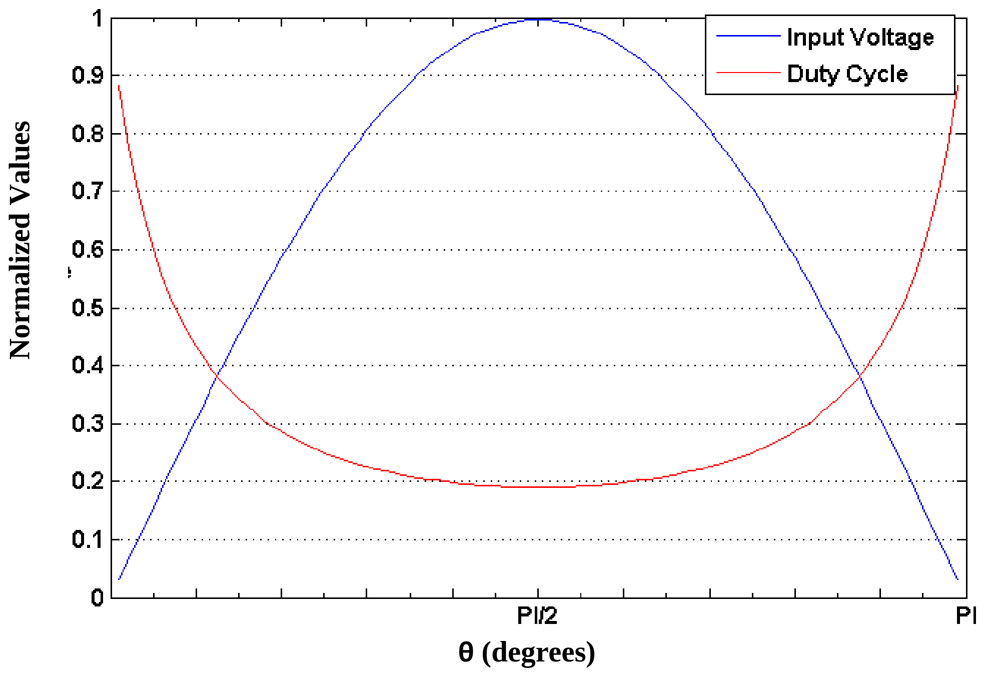


Figure 4.13 Input line voltage and duty cycle

4.3.2.2 Step 2: Passive Component Selection

In order to calculate the inductor values, first the ripple in the input line current has to be defined for the highest current value. Highest current value occurs at the peak voltage value which is 373 V in this situation. The equation 4.23 shows the peak value of input current;

$$I_l = \frac{2P_o}{V_l} = 0.3914 \tag{4.38}$$

Then the ripple at the line current is selected which affect the value of the primary inductance. The ripple of inductor current is 20 percent of primary current. The equation 4.31 calculates the inductor L_1 and equation 4.27 calculates the equivalent inductor L_{eq}. The equation 4.32 shows the calculation of inductor L_2.

$$L_1 = 820\, uH \tag{4.39}$$

$$L_{eq} = 73\, uH \tag{4.40}$$

$$L_2 = 82\, uH \tag{4.41}$$

Other passive elements are the capacitors of the SEPIC converter. This capacitor is calculated by choosing a low-frequency oscillation between the passive elements. This value has to be chosen with respect to condition at the 4.33 and calculated to be;

$$\omega_r = 16.740\, kHz \tag{4.42}$$

$$C_1 = 100 \text{ nF} \tag{4.43}$$

Capacitance of C_{in} has to be a small because it follows the input voltage waveform without storing energy. C_o reduces the low frequency ripple in the output voltage. Equation 4.34calculates C_{in} and by assuming the output voltage ripple as 10%, C_o is calculated by the equation 4.35.

$$C_{in} = 420\, nF \tag{4.44}$$

$C_o = 330$ uF (4.45)

4.3.2.3 Step 3: Active Components Selection

The active components of the converter are the PWM controller, the switch and output diode. Proposed converter introduces PWM controller [35] as ISL6745. The switch is a MOSFET with unique features. The output diode is a fast diode again selected with respect the properties of the converter. This part includes the active components parameters and calculations.

4.3.2.3.1 ISL6745, Bridge Controller with Precision Dead Time

ISL6745 is a PWM controller with various features produced by IC manufacturer *Intersil*. Most powerful feature is the precise frequency control and dead time control. This property also guarantees the DCM mode of operation. In addition, IC has soft-start operation, over-current shut-down and thermal shut-down properties.

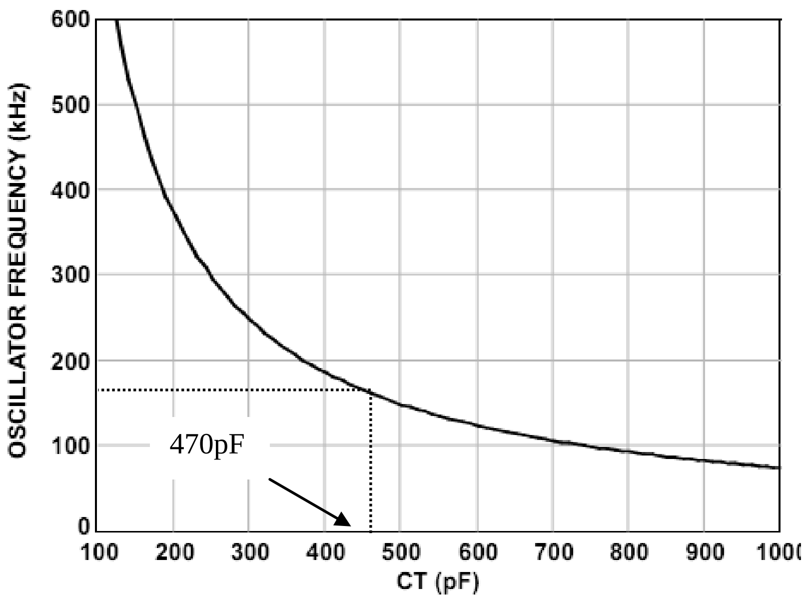


Figure 4.14 IC oscillator frequency value for different capacitance values [35, 5]

IC has an internal gate drive circuitry and can drive the MOSFET directly. Designer defines the switching frequency of the MOSFET. The switching frequency and dead time can be adjusted precisely with a capacitor (C_T) and resistor (R_{TD}). Converter switching frequency (f_s) is 150 kHz. Figure 4.14 shows the relation between circuit parameters to working frequency [35]. This function defines the frequency and capacitor value with respect to the value of R_{TD} = 49.9 kΩ.

These two parameters also define the dead-time period in the switching period;

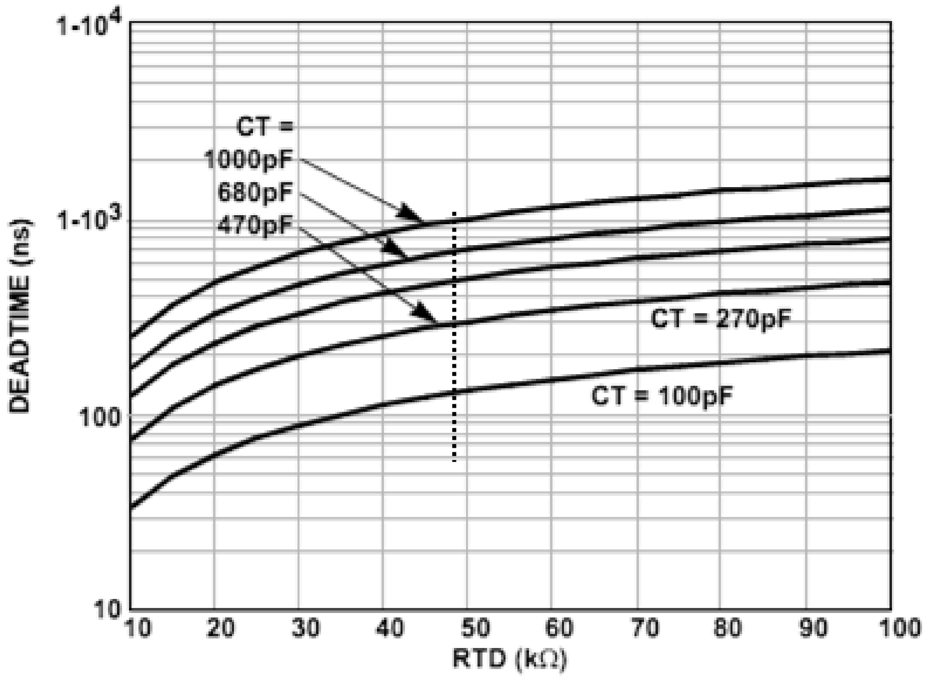


Figure 4.15 Dead-time of switching cycle for different resistance values for specific capacitance values

The values of these elements are selected; C_T as 470 pF and R_{TD} as 49.9kΩ. These values assure the operation mechanism as; switching frequency as 150 kHz and minimum dead time ($T_{dead-min}$) as 500ns.

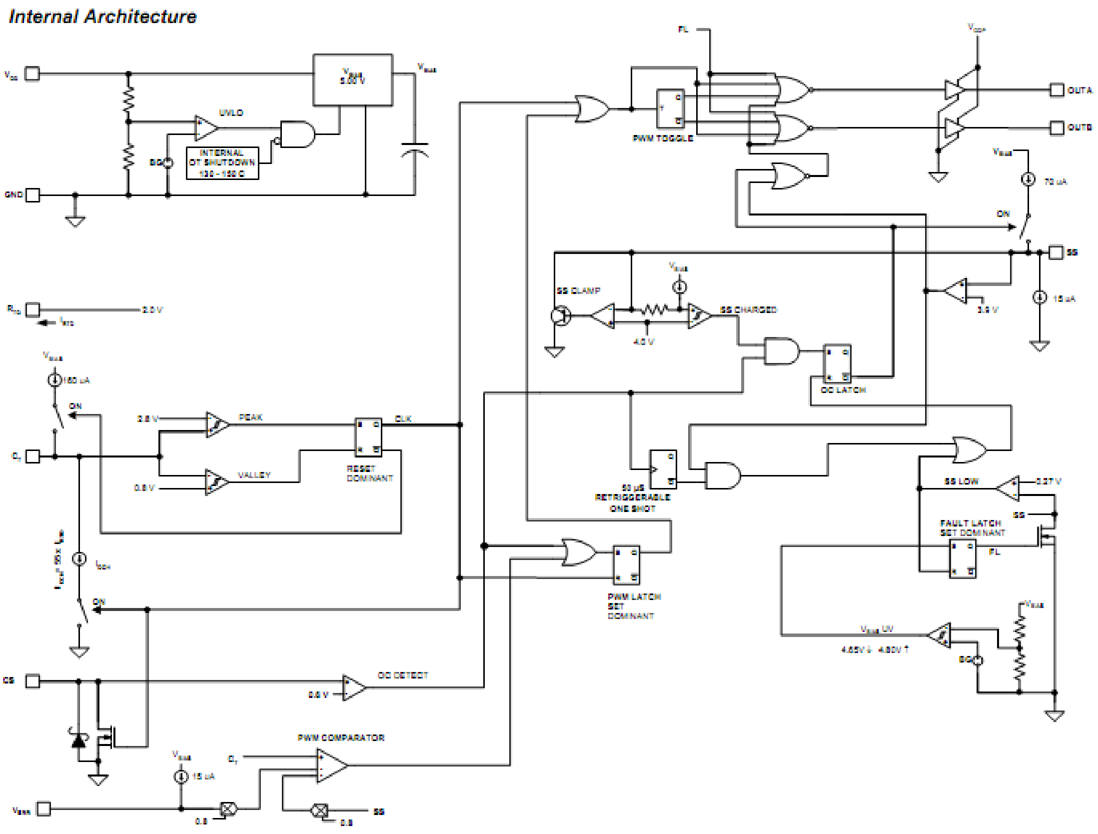


Figure 4.16 ISL6745 internal structure [35, pg2]

IC has 8-pin MSOP package, which brings the advantage of low size for both controller and the passive elements. Figure 4.16 details the internal structure of the IC. Next section details the working principle of the IC and the affects of the changes.

First part is the supply voltage (V_{dd}) which has an input voltage range of 0.3 V to 20 V. However, typical applications are in the range of 9-16 V. In order to supply the controller, designer introduces an extra circuitry in the converter. This supply voltage also defines the MOSFET drive voltage; if voltage is high the capability of the MOSFET gate voltage will be high and the current capacity will be high.

Second part is oscillator part; there is two pin as R_{TD} and C_T. As mentioned in the previous section C_T, sets the frequency of the oscillator. This signal oscillates between 0.8 and 2.8 V. The pin of R_{TD} has 2 V output, and a series resistor sets the discharge current. Also, these values define the dead time.

Third part is the *CS* and V_{err} pins of the IC; which are the control pins. *CS* pin senses the value of the MOSFET current. Series resistor to *source* pin of the MOSFET sense the current which is compared to an internal voltage of 0.6 V, if the voltage on R_c exceeds this voltage level IC introduces into an over-current mode and internal circuitry block the output gate drive.

The series resistor between the pin sense resistor and pin introduce a delay between external switch and internal clock. After every over-current operation a new start-up process begins. V_{err} pin controls the duty cycle of the PWM comparator; as the voltage level at this pin increases the duty cycle of the converter increases. An op-amp or an optocoupler can control this pin. In SEPIC converter, there is an error amplifier to control this pin. The control voltage changes in order to change the duty cycle value of the converter with respect to the error at the current value of the LEDs. Fourth part is the gate drive circuitry of the IC as *OUTA* and *OUTB* whose have opposite values with respect to the other. These pins are capable to source of 1 A peak current. The gate drive circuitry looks for the condition of over current. If there is an over current situation, controller moves in a fault condition and starts a *soft-start*. If there is no fault condition, IC activates the output gate drive signal. Output current (I_{out}) of the out pin can be calculated by the equation 4.49. In this equation Q stands for loading capacitance value and f_s shows the switching frequency as mentioned in previous part.

$$I_{out} = 2 * Q * f_s \tag{4.46}$$

Final part is the *SS* pin of the IC which introduces delay during start-up. *SS* pin can switch on or off the IC and stops the converter operation. This pin can be used as an over-voltage controller in order to stop the converter operation in any case of overvoltage operation in the converter.

The IC has an over temperature control, which cause the IC to stop the operation in any over-temperature case. It has a thermal resistance ($\theta_{a\text{-}j}$) the value for junction to ambient as 128 °C/Watt. If the ambient temperature (T_a) is 45°C and temperature at the junction point of

IC (T_j) is 115 °C. The equation 4.49 shows the maximum allowed power (P) that can device dissipate.

$$P = \frac{T_j - T_a}{\theta_{a-j}} = \frac{115-45}{128} = 0.54\ W \tag{4.47}$$

4.3.2.3.2 MOSFET Selection

SEPIC converter uses Power MOSFET (**M**etal-**O**xide-**S**emiconductor-**F**ield-**E**ffect-**T**ransistor). MOSFETs are, developed transistors and have different properties from Bipolar Junction Transistors (BJT). MOSFETs are voltage driven transistors, have faster switching time and have simple gate drive circuitry. They are manufactured as n-type or p-type, and gate pin is isolated from the semiconductor structure. MOSFETs are three terminal devices; gate, source, drain. MOSFET selection has to be performed systematically in order to use efficient and obtain a cost effective solution. This part involves the calculation steps.

First step is to calculate the maximum voltage on the MOSFET during the converter operation. This will define the maximum drain to source voltage (V_{DS-max}) of the MOSFET, which occurs at the highest input voltage (V_{in-max}) value is calculated by;

$$V_{DS-max} = V_{in-max} + V_o \tag{4.48}$$

$$V_{DS-max} = 440\ V \tag{4.49}$$

The voltage on drain-source (V_{DS}) changes with respect to the change in the input voltage waveform and there is not an extra voltage on the MOSFET with respect to converters operation. Therefore, choosing a MOSFET with a rating of 600 V will be a reasonable choice.

Second step is to calculate the current ratings of the MOSFET. The drain current of the MOSFET in this converter is not continuous, which have duration as on-time of the switching period. The equation 4.7 calculates switch current and peak value of switch current (I_{q-p}) is calculated at the highest input voltage in (4.53);

$$I_{q-p} = 5.1\ A \tag{4.50}$$

The equation 4.54 calculates the root-mean-square (RMS) value of the switch current ($I_{q\text{-}av}$);

$$I_{q-av} = \frac{I_{q-p}T_{on}}{2T_s} = 0.4A \tag{4.51}$$

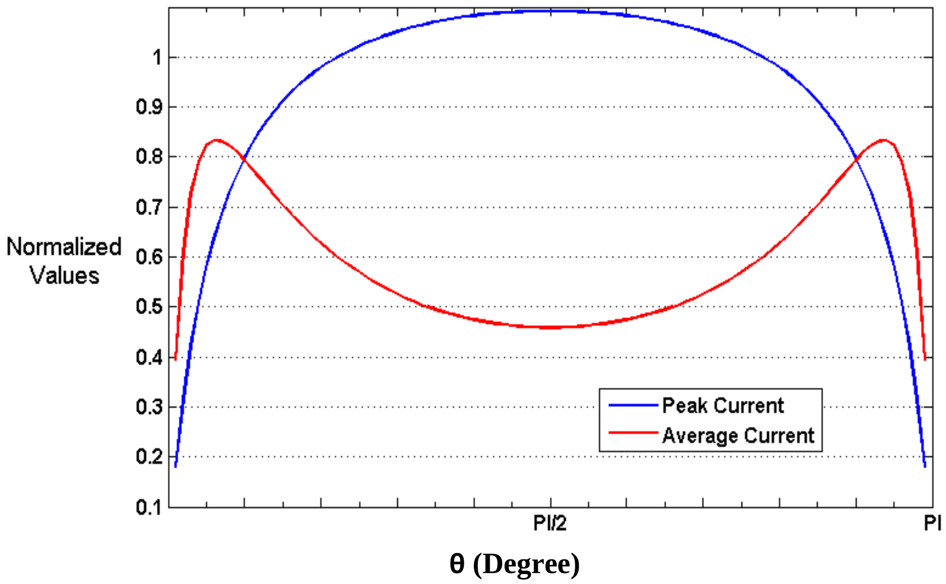


Figure 4.17 MOSFET peak current and average current, normalized values

Figure 4.17 illustrates the peak current values and average current values of MOSFET. Here, MOSFET peak values changing with respect to the change of the input voltage waveform.

Next step is defining the gate charge value of the MOSFET. The gate charge can be calculated by re-arranging the equation 4.49;

$$Q = \frac{2 * I_{OUT}}{f_s} = 13\ \text{nC} \tag{4.52}$$

Final step is to calculate the power dissipation of the MOSFET. In order to calculate the power dissipation, the MOSFET has to be selected. The previous calculations define the basic parameters of MOSFET. In addition, there are various types of MOSFET that provides these properties. If designer use a MOSFET with low on resistance (R_{DS-ON}) value, the dissipation will decrease. However, the cost of the MOSFET will increase. At this point, it is the choice of designer to use high price device or use a low price device with brings another component to transfer the heat, and using a propoer heat-sink.

Researchers chose the MOSFET as SDP03N60C3 (Cool MOS Power Transistor) from *Infineon Technologies* company which is detailed in Table 4.2. Device is available both for SMD TO-252 package and dip package TO-251. Loss will be calculated at different modes of operation.

Table 4.2 MOSFET, SDP03N60C3 properties

Property	**Symbol**	**Value**	**Unit**
Drain-Source Breakdown Voltage	$V_{BR(DSS)}$	600	V
Drain-Source on Resistance	$R_{DS(on)}$	1.4	Ohm
Continuous Drain Current	I_D	3.2	A
Gate Charge Total	Q_G	13	nC
Thermal Resistance (junction to case)	R_{thJC}	3.3	K/W
Thermal Resistance (junction to ambient)	R_{thJA}	75	K/W
Total Power Dissipation	P_{tot}	38	W

The RMS value of the MOSFET current, I_{q-rms} is calculated by using MATLAB. Equation 4.7 defines the current function of the MOSFET. At each switching cycle, the peak value and the duty cycle changes; therefore each switching cycle divided into 100 pieces also the one line period divided to 100 pieces and the resultant wave-shape obtained by MATLAB is shown in figure 4.19.

MATLAB calculates the RMS value of this wave-shape functions and $I_{q-rms} = 1.35\ A$. (MATLAB code is in the appendix a.3)

Next calculations will be performed in order to obtain the loss of the MOSFET. First is the on-time loss (P_{on}) of the MOSFET which is calculated in equation 4.56 and 4.57.

$$P_{on} = I_{q-rms}^2 \times R_{DS(on)} = 2.25\ W \tag{4.53}$$

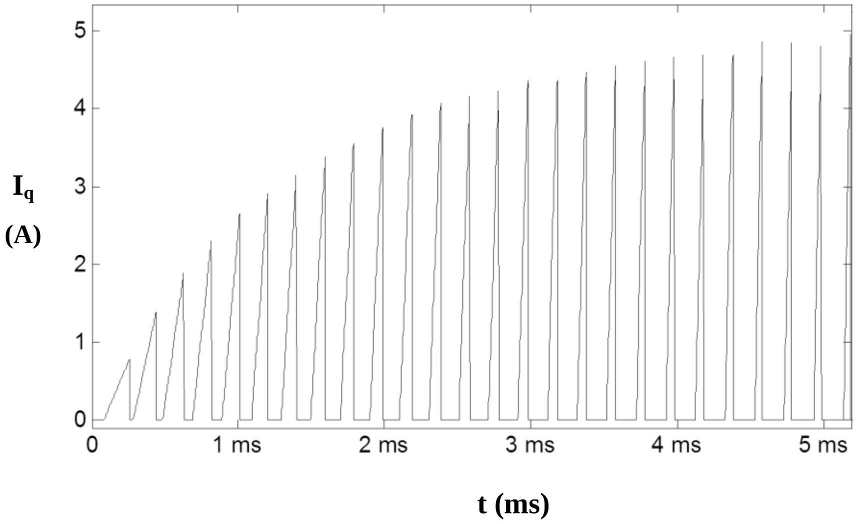


Figure 4.18 MOSFET current waveform for quarter line cycle

Second power loss is the switching power losses (P_{sw}), turn-on and turn-off.

$$P_{sw} = \frac{1}{2} I_{q-rms} V_{DS}\ \ t_{on} + t_{off}\ \ f_s = 3.5\ W \tag{4.54}$$

Total loss of the MOSFET (P_D) is the sum of the two equations which is;

$$P_D = P_{on} + P_{sw} = 5.77\ W \tag{4.55}$$

If MOSFET is used without heat-sink at ambient temperature (T_a) of 25°C, junction temperature (T_j) is calculated in (4.59) where R_{thJA} denotes thermal resistance from junction to ambient of MOSFET.

$$T_j = T_a + P_D R_{thJA} = 450\ °C \tag{4.56}$$

Therefore, there must be a heat-sink in order to transfer the heat without harming the MOSFET. Here, T_j assumed as 115 °C maximum and thermal resistance of the heat-sink (R_{thh}) can be calculated by,

$$R_{thh} = \frac{T_j - T_a}{P_D} - R_{thJA} = 13.6\ K/W \tag{4.57}$$

4.3.2.3.3 Diode selection

The diode of SEPIC converter can be thought as secondary switch of the converter. In the second mode operation, the current flows from the diode with a similar waveform of MOSFET current.

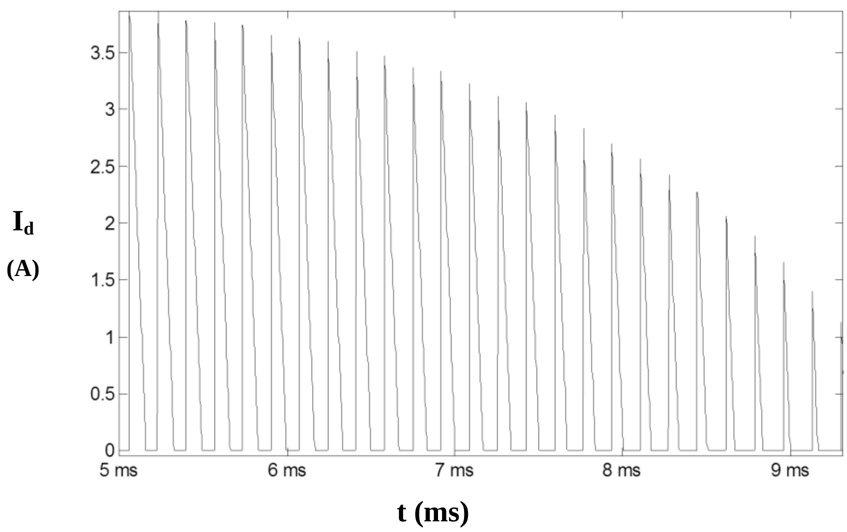


Figure 4.19 Output diode current waveform in a half-line cycle period

First step is to calculate the voltage and current ratings of the diode. Equation 4.61 calculates the maximum voltage rating (V_{dmax}) of the diode:

$$V_{dmax} = V_l + V_o = 380\ \text{V} \tag{4.58}$$

Second is the current rating of the diode; by using the same method for MOSFET's current calculation, MATLAB developed diode current waveform. The equation 4.10 defines the diode current. MATLAB calculates the RMS value as 1.3027 A. Diode is 1N5418 from *"Vishay Semiconductor"*, which is *a* fast avalanche rectifier. Table 4.3 defines the properties of the diode.

Equation 4.62 calculates the loss of the diode, by multiplying the forward voltage drop (V_f) and RMS value of forward current (I_{drms}).

$$P_D = V_f \times I_{drms} = 1.43\ W \qquad (4.59)$$

Table 4.3 Diode 1N5418 properties

Property	**Symbol**	**Value**	**Unit**
Maximum Peak Reverse Voltage	V_{RRM}	600	V
Average Forward Current	I_{av}	3	A
Forward Voltage	V_f	1.1	A
Gate Charge Total	Q_G	13	nC
Thermal Resistance (Junction to Ambient)	R_{thJA}	25	K/W

Equation 4.63 calculates the junction temperature, by the power dissipation and the thermal resistance value.

$$T_j = T_a + P_D R_{thJA} = 60°C \qquad (4.60)$$

Therefore, these are the active elements of the converter. Designers choose the other passive elements like resistors with respect to the power ratings and the tolerance values.

Next section involves the converter simulation, in order to test the voltage and current ratings, converter working principle and converter input and output; voltage and current values investigation.

4.4 Implementation of SEPIC Converter by Computer Simulations

In this chapter converter simulation will be performed by using program Simplorer v7.0 by *Ansoft*. Converter electronic components are the parts from the program's library. The active devices, MOSFET and diodes are defined with respect to their properties. The library does not contain the IC like the one used in SEPIC converter. The program uses equation blocks in order to use PWM converter. The equation blocks constitute the internal structure of IC.

4.4.1 Simulation Application of SEPIC Converter

Figure 4.20 presents the simulation schematic and Table 4.4 details the simulation and converter parameters. The controller circuit has input signals as; output voltage, MOSFET current, and LED current. Output voltage current is used for overvoltage protection (OVP). The principle is dividing voltage by a voltage divider circuit and the obtained voltage is compared with a reference voltage with in an op-amp. If the voltage obtained is higher than the reference voltage, means that there is an over-voltage condition. As a result, converter stops the operation directly and waits for the condition to recover. Second signal is the MOSFET current signal; by using a resistor connected series to MOSFET source. (It can be sensed directly in the simulation, this way is preferred to have the same circuit with application circuit).

The current value defines the over-current situation of the circuit. The value is compared to a reference value similar to OVP control, and if the voltage on the resistor (the current value of MOSFET) exceeds the reference value the control system stops the operation until the situation recovers. These parts are the protection parts of the control circuit. The main control is the control of the LED current and changing the duty cycle.

The purpose of the simulation is to investigating the operation mechanism of the converter and confirming the resultant waveforms with the analytical calculations.

Table 4.4 SEPIC converter simulation parameters

Parameter Description	Abbreviation	Value	Unit
Simulation Maximum Step size	H_{max}	0.1	ms
Simulation Run Time	T_{end}	100	ms
Integration Formula		Trapezoidal	
Power Stage Parameters			
Input Line Voltage	$V_{in,rms}$	110-220	V_{rms}
Inductor 1	L_1	820	uH
Inductor 2	L_2	82	uH
SEPIC Capacitor	C_1	100	nF
Input Capacitor	C_{IN}	240	nF
Output Capacitor	C_o	3.3	uF
Control Parameters			
Current Sense Resistor, MOSFET	R_s	0.12	Ω
Current Sense Resistor, LED	R_c	3.5	Ω
OVP Resistor,1	R_{o1}	1	kΩ
OVP Resistor,2	R_{o2}	65	kΩ

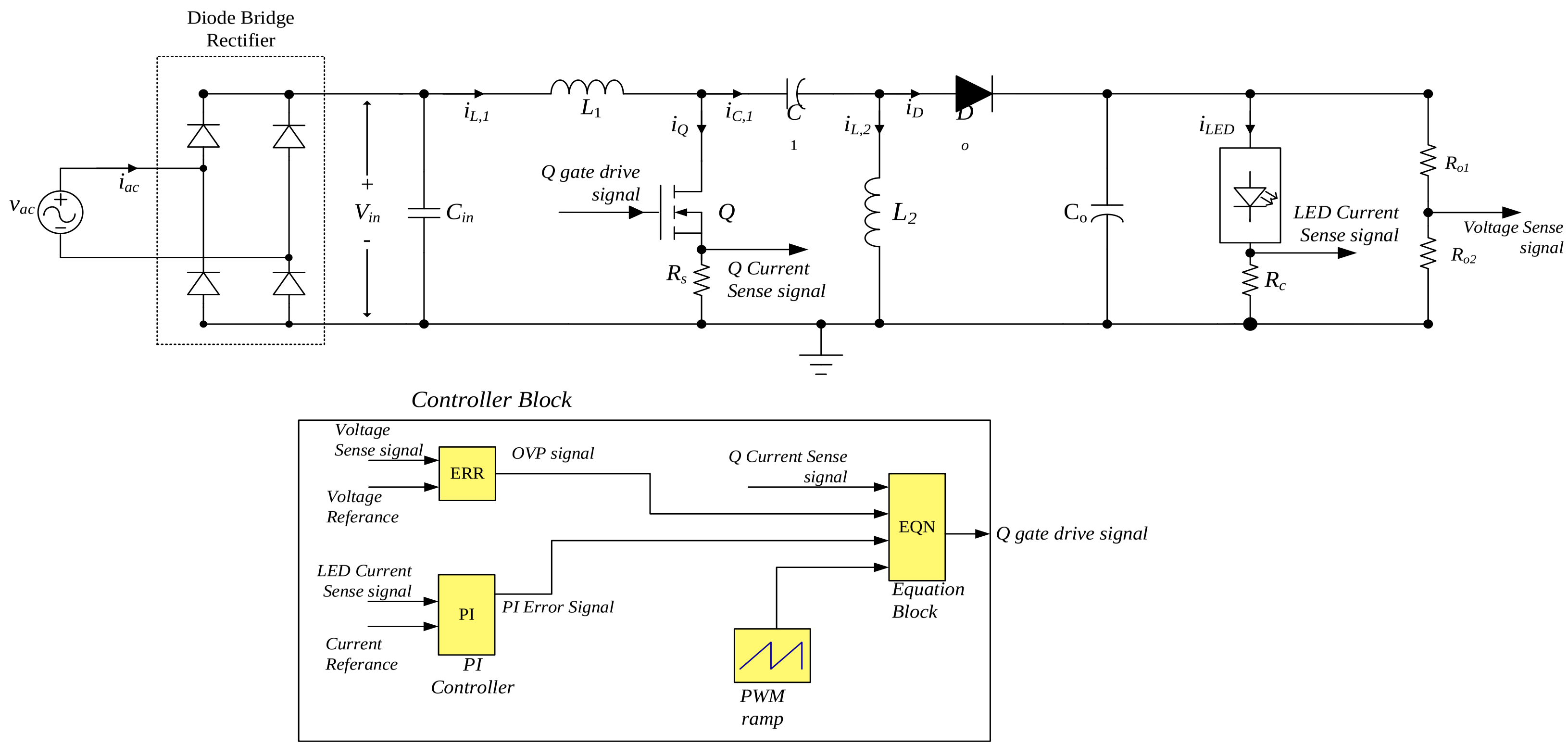


Figure 4.20 SEPIC converter simulation application circuit

4.4.2 Simulation Results of SEPIC Converter

This part introduces the characteristic waveforms of the SEPIC converter.

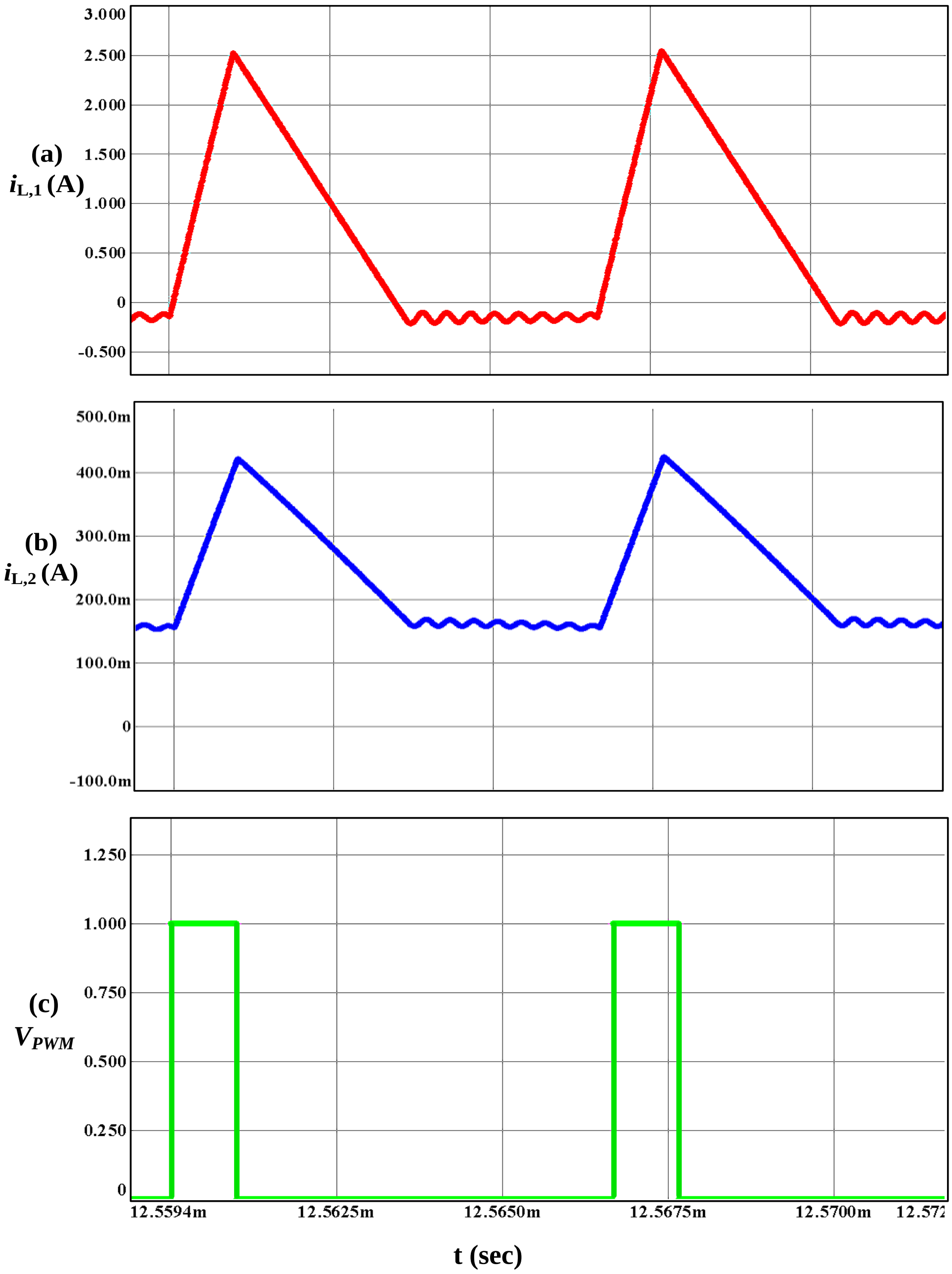


Figure 4.21 SEPIC converter characteristic waveforms:
(a) primary inductance current, (b) secondary inductance current, (c) PWM gate drive signal

Figure 4.21 introduces the inductor current and PWM gate drive voltage waveforms within the limits of switching cycle. As it is proposed from analytical calculations and proposed working principle; inductors work in DCM mode of operation. Their initial values are equal just opposite value because of the current directions. The current values rise when the MOSFET is in on position and after that they release all of the stored energy on their core.

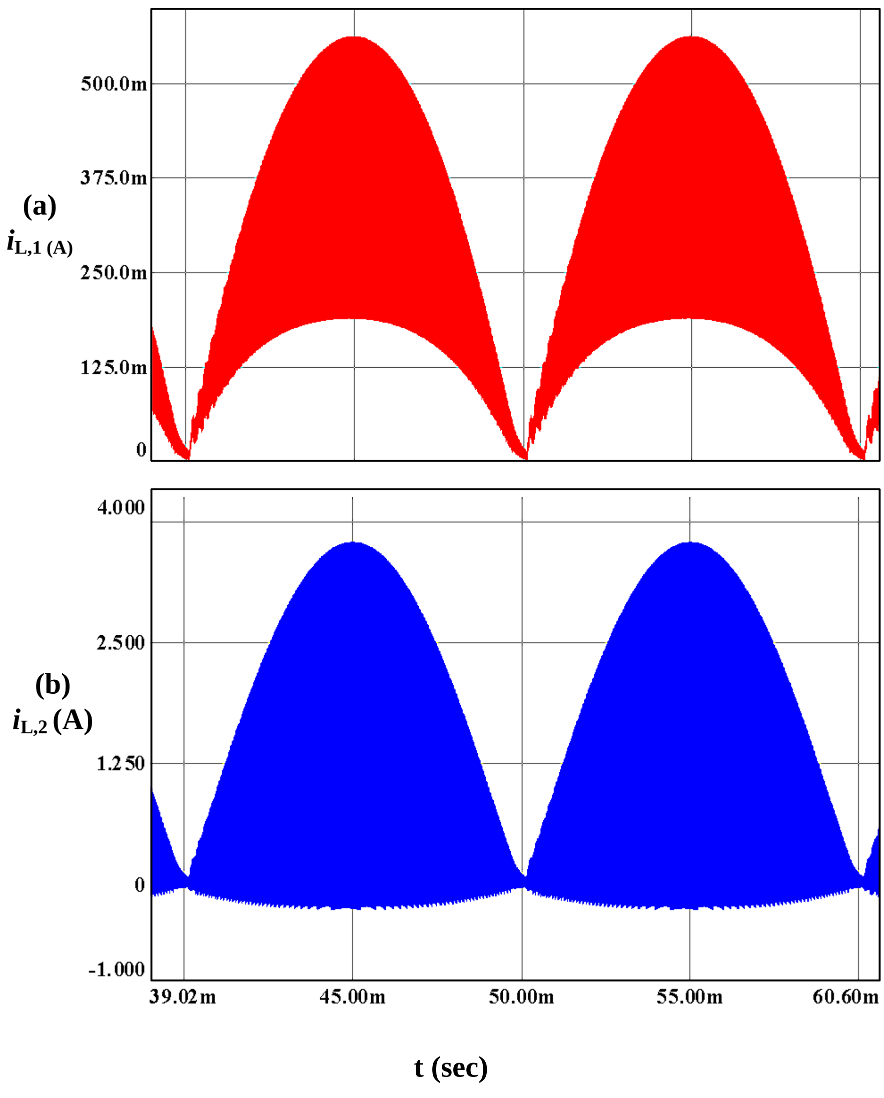


Figure 4.22 SEPIC converter characteristic waveforms with line period
(a) primary inductor current waveform (b) secondary inductor current waveform

The peak values of the current waveforms are changing with respect to input voltage. This is illustrated in figure 4.22. In these figures the primary inductor current also equals to the diode rectifier current. Here, the duty cycle of the converter also changes with respect to input line voltage. The value of duty cycle decreases as the input voltage increases, unlike the inductor peak current values. Next part shows the MOSFET current, i_Q and output diode current, i_D. The current values of theses active devices prove the mode of operation. Figure 4.23 illustrates the three time period. In the first part, MOSFET current increases, when MOSFETs on state, when it moves to off position the second state begins; MOSFET current directly goes to zero and output diode current start to rise. The peak voltage value of MOSFET and diode are same. This state finishes when the inductors release their energy and then the final state starts. In this state, both MOSFET and diodes are in off mode, and this dead time guarantees the DCM mode of operation. MOSFET current is total of two inductor currents.

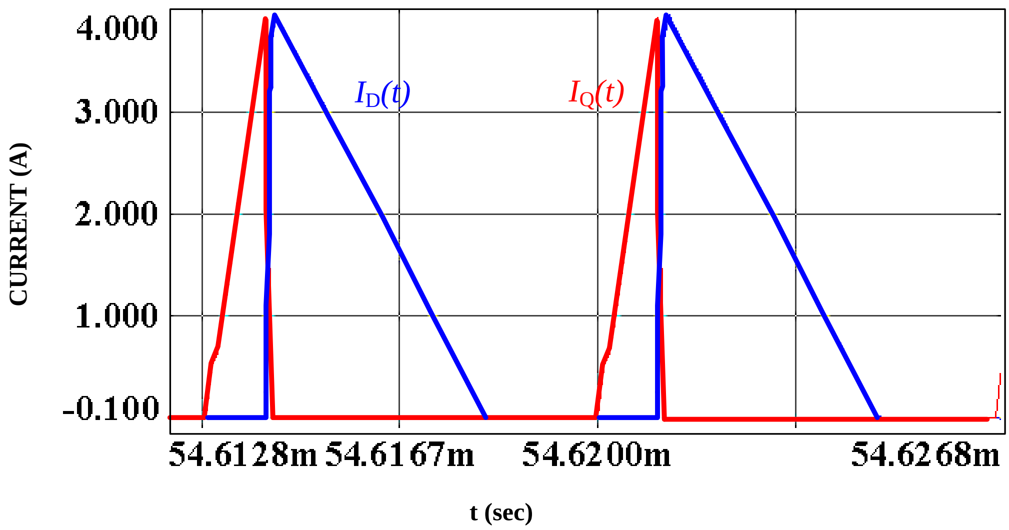


Figure 4.23 SEPIC converter characteristic waveforms MOSFET current (red), output diode current (blue)

Figure 4.24 shows the voltage value of the MOSFET’s drain to source, the input capacitors voltage value and the SEPIC capacitors voltage. As it is stated in the analysis of the converter the input capacitor and the SEPIC capacitor are not for energy storage. They have to have equal voltage for correct operation. The MOSFETs voltage waveform follows the input capacitors voltage waveform. This voltage value is different from peak input voltage value, because the voltage on D-S of MOSFET is the sum of the input and output voltage.

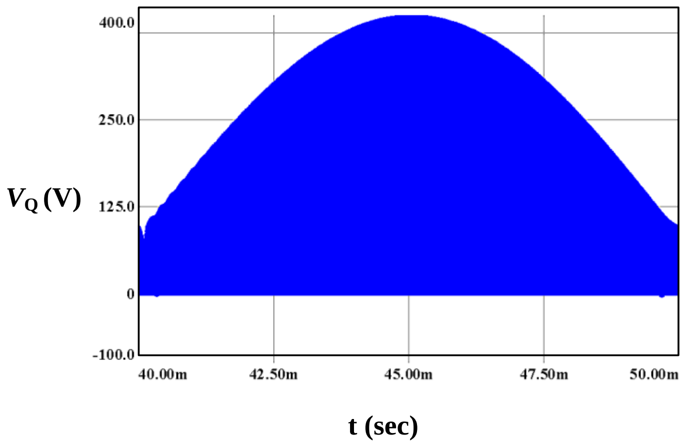


Figure 4.24 SEPIC converter; MOSFET D-S voltage waveform

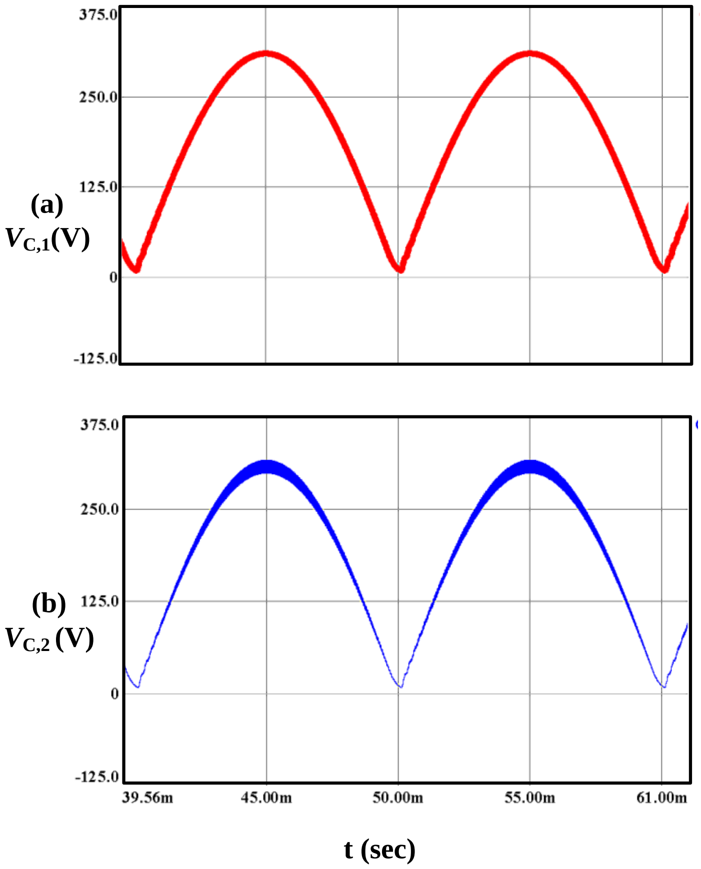


Figure 4.25 SEPIC converter: (a) input capacitor voltage
(b) SEPIC capacitor voltage waveform

Next part is the output stage of the converter; LED current and output voltage waveforms. As it shown in the analysis of single stage power supplies, the output waveforms have an oscillation in the twice of the line frequency. Output voltage and output current waveforms oscillates at the twice frequency of line frequency. The current value has a peak-to-peak ripple of 35 percent of the average output current value. The average current value is 350 mA and the average output voltage is equal to 72 Volts. The voltage and current ripple can be decreased by using a larger capacitor value or changing the inductor values.

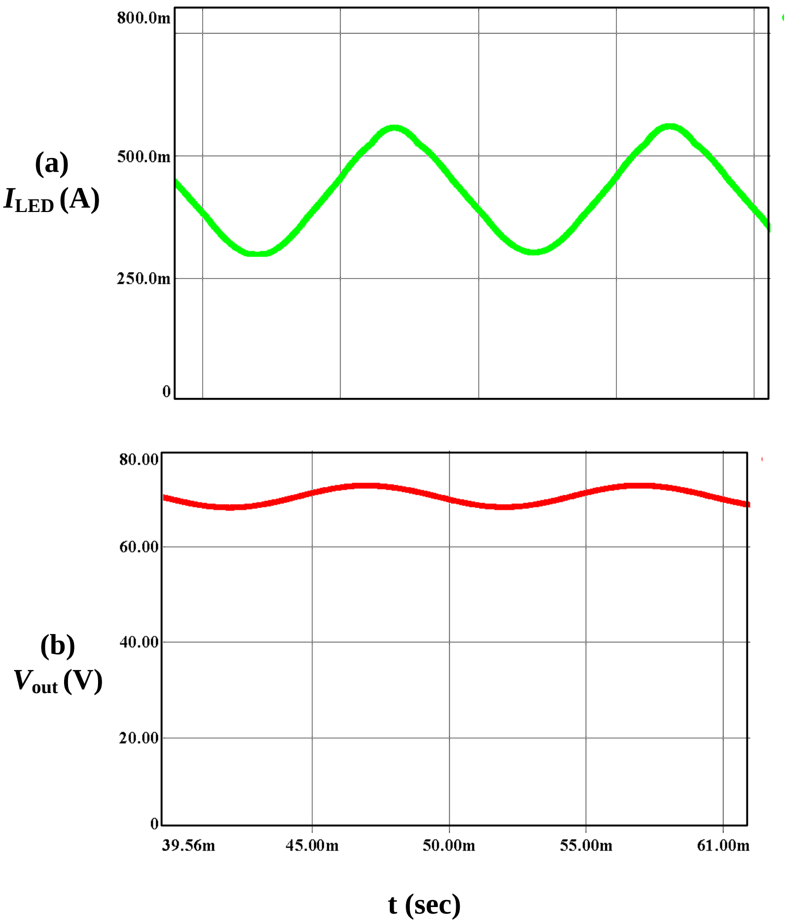


Figure 4.26 SEPIC converter: (a) LED current waveform, (b) output voltage waveform

Final stage is the performance simulations of the converter. Figure 4.28 introduces the input voltage and input current waveforms. Than the power quality parameters are power factor (PF), total harmonic distortion (THD). *Day Post Processor* (module of the Simplorer) calculates these values.

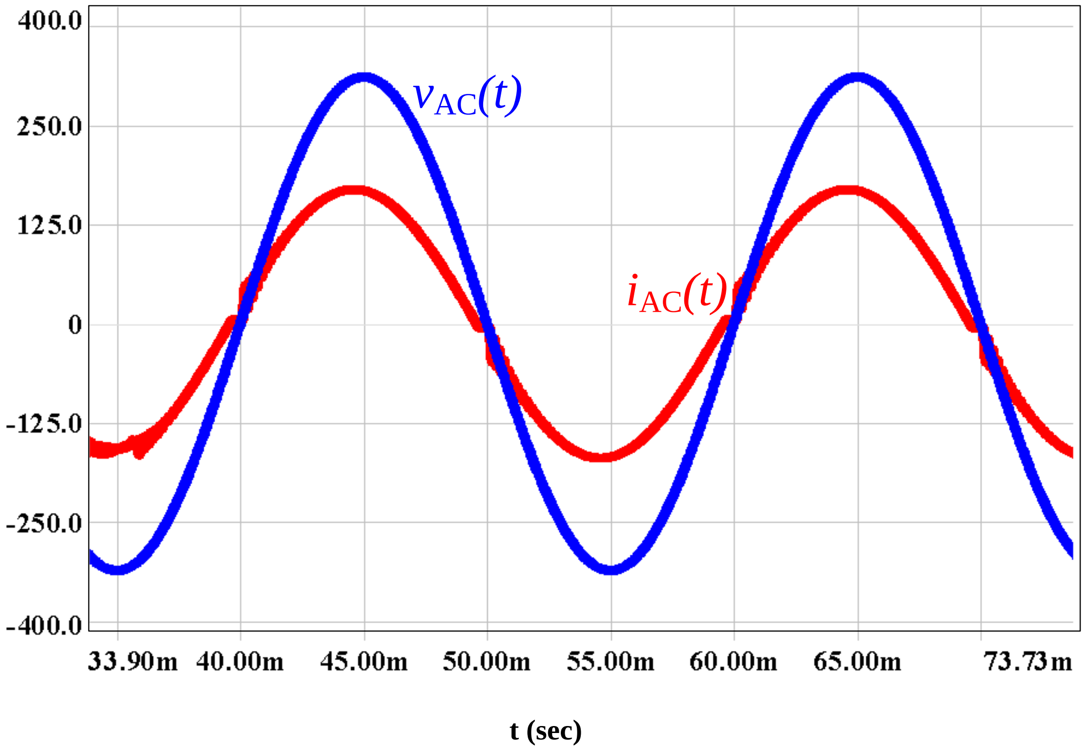


Figure 4.27 SEPIC converter; input voltage (blue), input current(red) waveforms

Here, the input line current follows the input line voltage which proves the principle of operation. However, there is still a phase difference between two waveforms which affects negatively the power factor. The measured value for PF is 0.98 and for the maximum loading condition is 0.99. Figure 4.28 illustrates the line current harmonic.

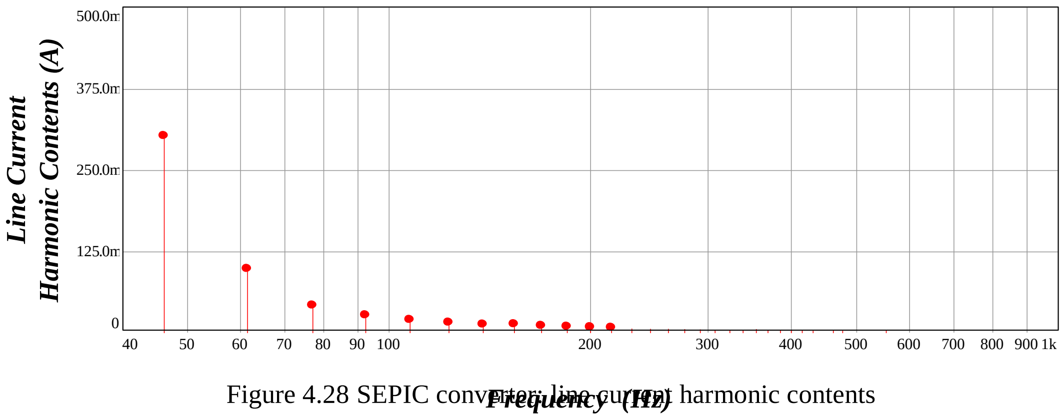


Figure 4.28 SEPIC converter; line current harmonic contents

4.5 Manufacturing and Experimental Verification of Single Stage SEPIC Converter

First part of this section covers the manufacturing the SEPIC converter, by designing the printed circuit board and assembling the electronic components. Second part includes the experimental verification of the converter. Manufactured product has to provide several features like protection and performance in addition to the basics of converter. Therefore, verification must include loading tests, input voltage tests and performance tests. Converter has to resist to failure conditions; short circuit situation, open circuit situation, input line voltage spikes.

4.5.1 Manufacturing the Single Stage SEPIC Converter

The beginning point is the printed circuit board design of the converter by circuit programs as Altium Designer. Altium Designer, is a circuit design program, involves schematic design, PCB design. The process on Altium design involves; defining all of the circuit elements in the library of the program, and drawing the circuit schematic with the design elements. Here, defining the elements is essential to have true shape on the PCB. Next stage is designing the PCB, by converting the schematic to a PCB. Program introduces several features which eases the design of the PCB. However, designer has to allocate the electronic components and define all of the parameters like, trace width, trace length, trace layer. PCB design is a detailed process and very important for the correction operation of converter.After, finishing the PCB design, the board has to be manufactured by individual manufacturers. Designer defines the board type, board thickness, copper thickness on the board and color of the board. The table 4.5 details the board properties;

Table 4.5 PCB properties

Property	**Parameter**
Board Type	FR-4
Copper Thickness	70 um
Board Color	Green
Board Thickness	1.6 mm

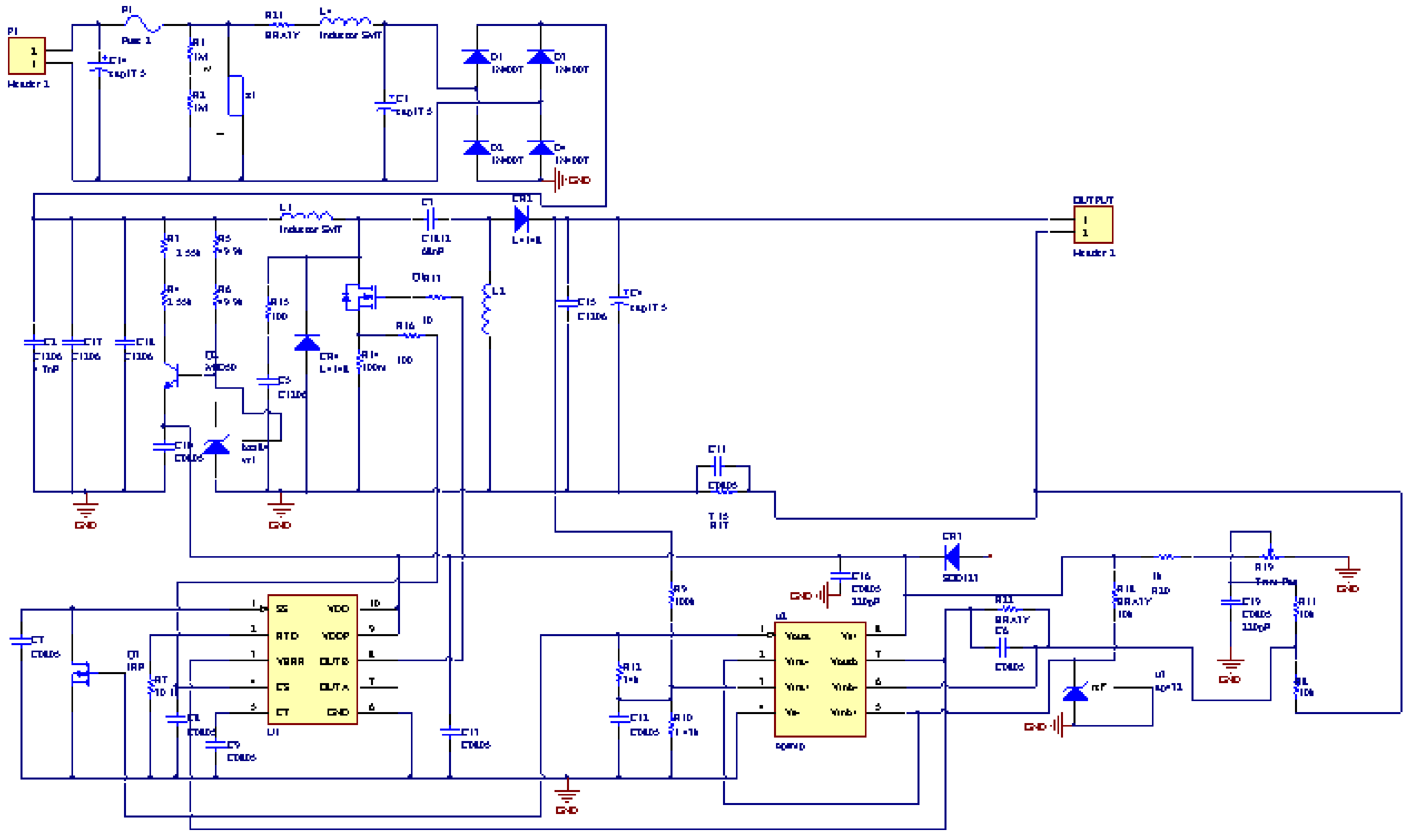


Figure 4.29 SEPIC converter schematic

The manufacturing process continues with assembling the electronic components. This process involves several tests and implementation with several steps. SEPIC converter implementation is performed with in this manner and the results are obtained. SEPIC converter is designed for universal input. Therefore, performance tests involve low-line input and high-line input voltages. Also, the loading conditions are tested for different voltage levels. Researchers propose 0.99 power factor at full-load and further performance values at different loading conditions. The experiments verified high power factor as the statements of researchers. The following figures are the photographs of the experimental circuits.

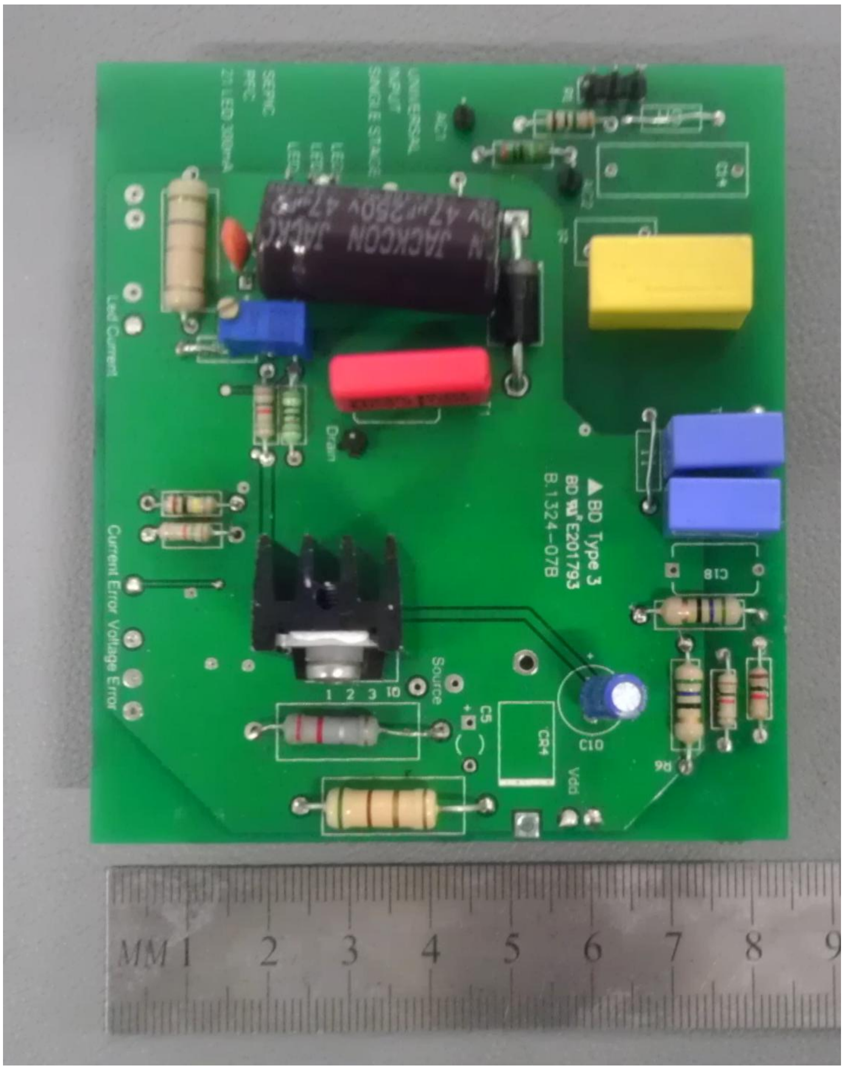


Figure 4.30 SEPIC converter top layer

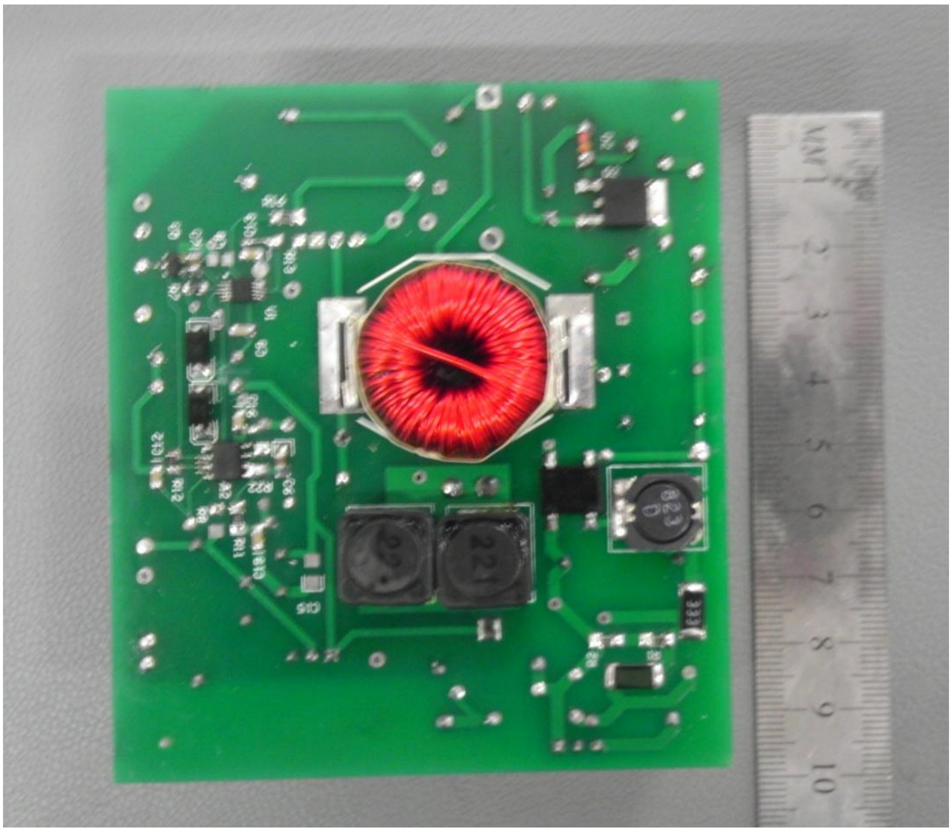


Figure 4.31 SEPIC converter bottom layer

4.5.2 Experimental Results of SEPIC converter

Experiments verified that SEPIC has converter is proper for LED application and converter has high performance in the manner of power factor and THD values. Converter is tested for different input voltage levels, for different loadings. In addition to performance analysis, some safety tests are performed like measuring the hot-points and operating the converter for a long-time. Even the converter design is performed in the manner of analytical calculations, from the first version of the converter; the results are satisfying. PCB design is renewed after first version, by changing some components layouts and changing the component locations. In the improvements some circuit elements are added with respect to measured noise and ripple effects. After improvements second version has lower loss, better performance and safer with respect to peak voltages.

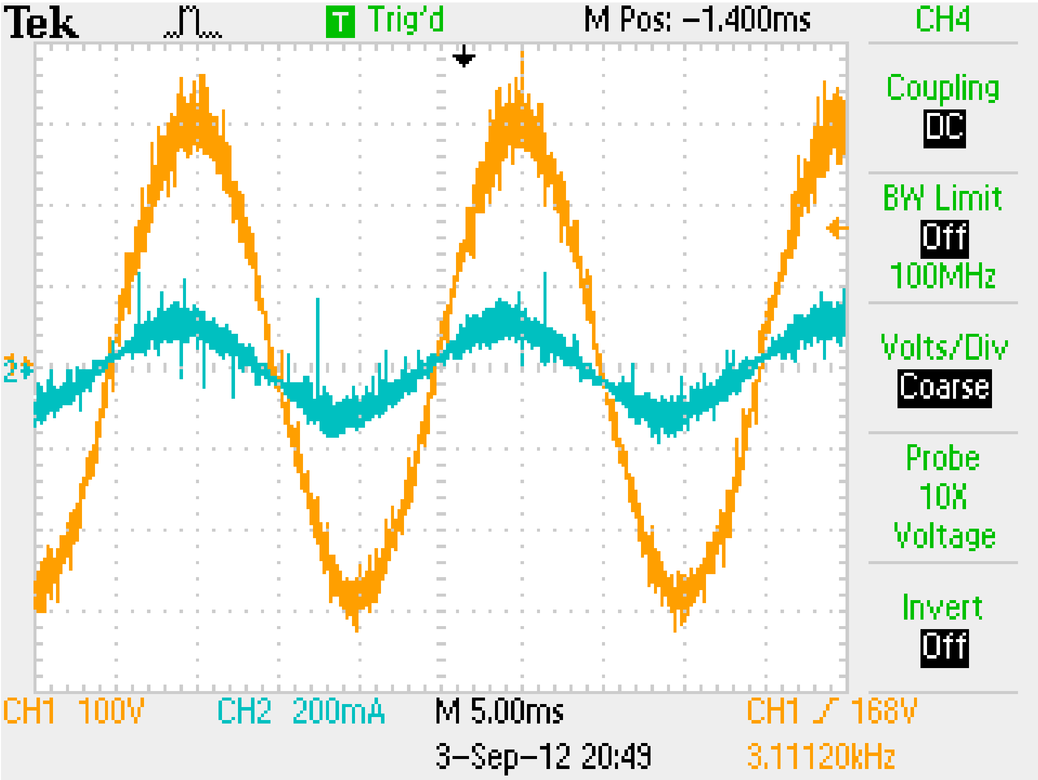


Figure 4.32 SEPIC converter Vin = 110 V; input line voltage (yellow) and input line current (blue) at 30W output power (Scales:100 V/div, 200 mA/div, Time: 5 ms/div)

First measurements are the input voltage waveform and input current waveform of the converter low line grid voltages as shown in figure 4.33. This test is performed at full load condition and the performance values are power factor 0.95, THD_i 4.3%.

Second test is performed for low high line grid voltage, and performance values are: power factor 0.99, THD_i = 5% and output current is 0.35 as designed as shown in figure 4.34. In both measurements input line current have sinusoidal waveform and PF values are very high as expected. As shown in figures, input voltage waveform is distorted in the manner of ripple over it. The reason is the line voltage is changed with a variable transformer, and the effects are observed because of the problems on this device.

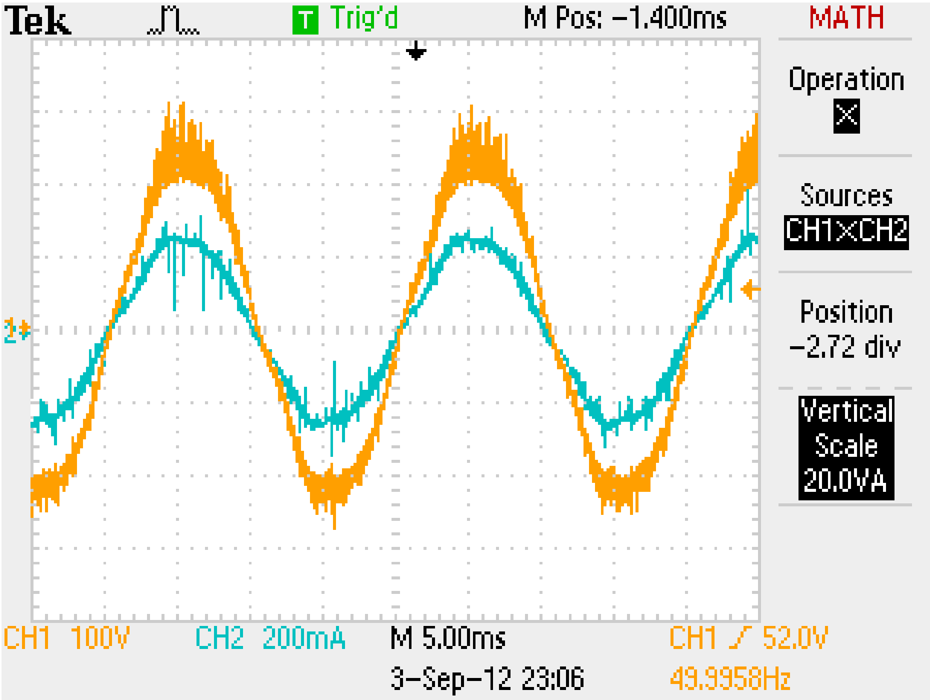


Figure 4.33 SEPIC converter at V_{in} = 220 V; input line voltage (yellow) and input line current (blue) at 30W output power (Scales:100 V/div, 200 mA/div, Time: 5 ms/div)

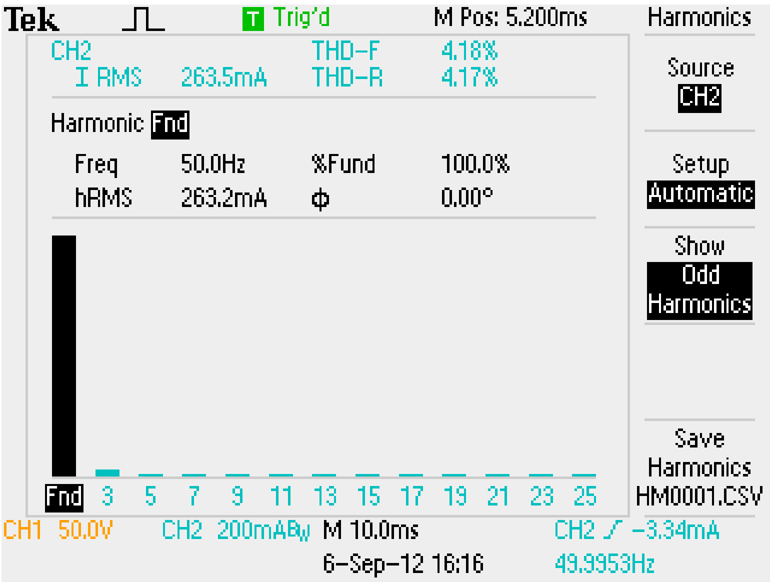


Figure 4.34 Harmonic analysis of SEPIC converter

Figure 4.35 shows the harmonic analysis of the converter and measured THD value for low line; input current is 4.18% and for high line this value is 4.8%. This limit is below the IEC 61000-3-2 standard for lighting equipment. This analysis is better than the proposed values of the researchers.

Next experiment shows the output voltage and output current of the converter in figure 4.36. As shown in figure the output current has a value of 350 mA as designed, and the ripple value is 236 mA. The output voltage also has a ripple on it with respect to the current value. As it is mentioned in previous sections, important thing is the maximum value of the current value and the oscillation frequency which is the double of the grid frequency. The oscillation is because of the topology of the converter. However, the magnitude of the ripple of output current is a result of the designs. This configuration is proper for LEDs, as the manufacturer states in their application notes. In the application the oscillation does not cause a light difference. Here, converter has to provide this operation every time of the operation. So these tests are performed for long time like one week and there is no change in the output current of the converter.

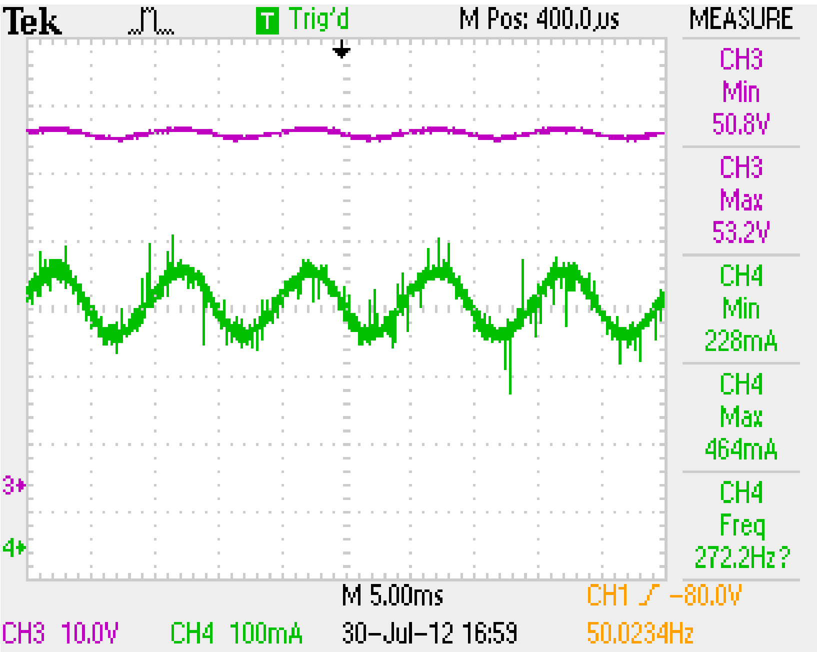


Figure 4.35 SEPIC converter output voltage (purple) and output current (green) at 20W output power (Scales: purple 10 V/div, green 100 mA/div, Time: 5 ms/div)

Next experiment details the converter power factor value changing with respect to different loads, at two input voltage levels which are detailed in figure 4.37. As shown in figure the worst value of the converter is 0.96 at lowest loading conditions. The power factor value decreases as the load of the converter decreases. The highest value is 0.995 for low line. Another value is 0.97 measured at 25 percent of loading condition; which is a very high value with respect to other configurations.

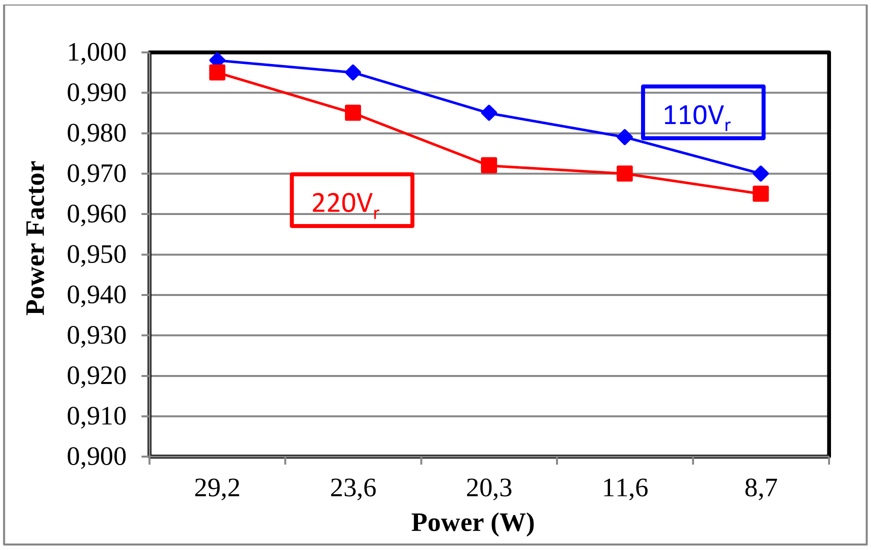


Figure 4.36 SEPIC converter power factor versus loading

The performance values show that the designed and manufactured converter matches with researchers proposed converter. In addition this converter provides high performance in the manner of power factor.

Next test is the efficiency change of the converter with respect to different loads. The load levels are; 100, 75, 50, 25 percent of loading. The converter efficiency is maximum 80 percent and minimum 75 percentage. Efficiency decreases as the loading decreases similarly to power factor change.

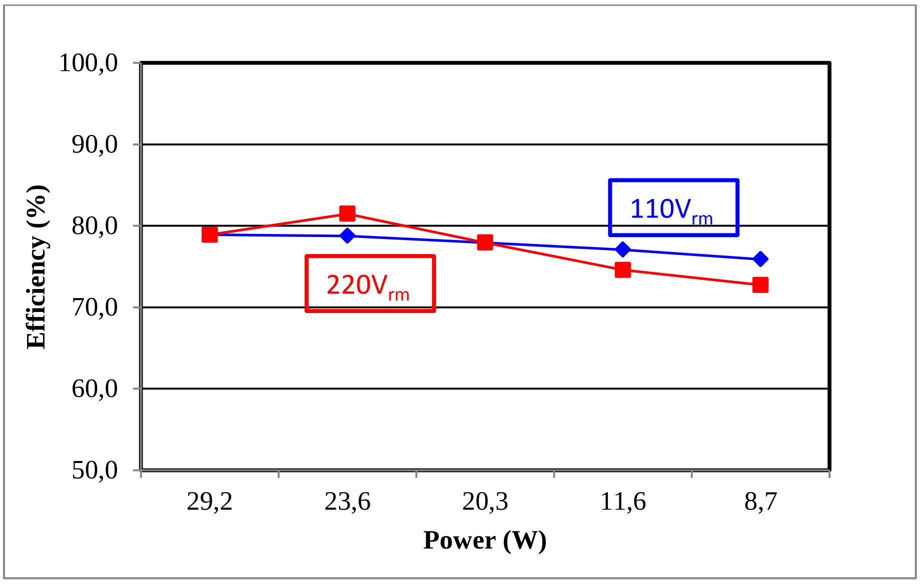


Figure 4.37 SEPIC converter efficiency versus different loads at different input voltage levels

Final test is the power factor change of the converter for different input voltage values. The test is performed for different load levels and the results are illustrated in figure 4.38. The worst condition occurs at minimum load at high voltage level, which is the value of 0.91.

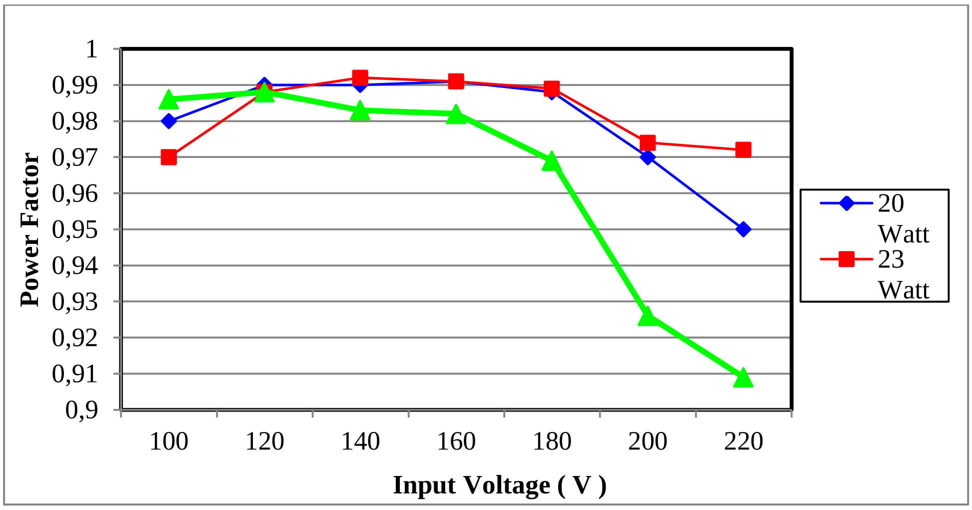


Figure 4.38 SEPIC converter power factor change due input voltage for different power levels

In these tests, loads are LEDs which is connected in serially. LED connection number is decreased in order to decrease the output power demand of the converter. All of the results are noted after a time of operation. Also the converter is tested for long-time operation and there is no heat-up problem of the converter.

4.6 Chapter Conclusion

This section finalizes the implementation of proposed single-stage SEPIC converter. This chapter introduced; SEPIC topology, analytical calculations, computer simulations and experimental verifications. Experiments and simulations verified the proposed SEPIC converter high performance and proper operation for LEDs. The resultant converter has high power factor with 0.995 in full power operation and in low-line input voltage. For high line operation, power factor value is again high as 0.99. Results show that; this converter is a high quality power supply for LEDs. Another main highlighting property is the output voltage has a high range, so it can be used in wide range of applications and there are few converters similar to this converter in the market. This converter provides this prime features with good performance and low cost. One drawback of the converter is low efficiency of the converter. Further work could be improving this converter, in the manner of efficiency and developing a commercial product capable for the standards.

CHAPTER 5

DESIGN AND IMPLAMENTATION OF SINGLE STAGE POWER FACTOR CORRECTED FLYBACK CONVERTER FOR LED APPLICATIONS

5.1 Introduction

This chapter introduces a distinctive flyback converter designed as a single-stage PFC converter for LED driver [26]. The first chapter introduces the properties and DC analysis of the flyback converter. Second part is the foundation of proposed converter and analysis of the operation modes. Next part involves the design steps, and selection of the converter parameters by analytical calculations. Next section continues with the verification of the proposed converter performance with the computer simulations. Final part is the experimental verification of the proposed converter.

Flyback converter is a transformer type converter which is a developed kind of buck-boost converter. The transformer used in flyback converters, also called as flyback transformer, works differently from ordinary transformers as the current flowing through the windings are not simultaneously.

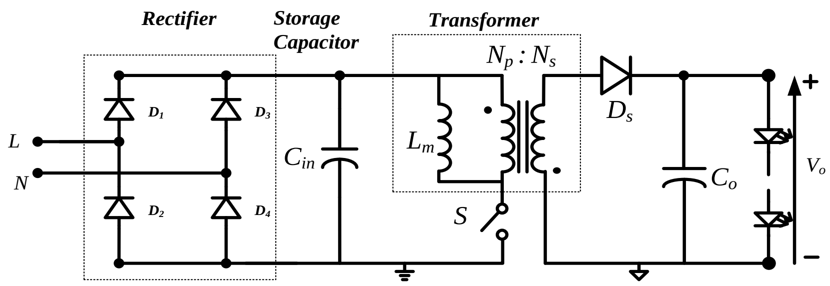


Figure 5.1 AC-DC Flyback converter

5.2 Single-Stage Flyback Power-Factor-Correction Power Supply

5.2.1 Introduction

The proposed converter is illustrated in figure 5.2 with key elements.

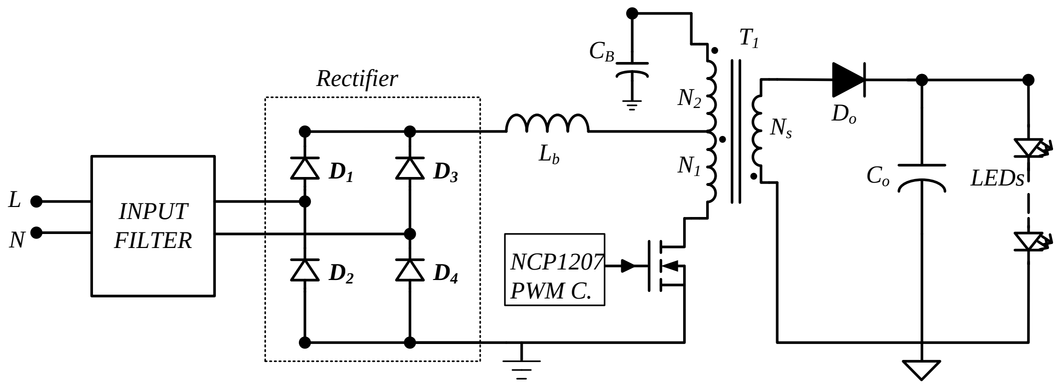


Figure 5.2 Single-Stage Flyback power-factor-correction front-end for HB-LED application [26]

The proposed converter includes a flyback transformer (T_1) with two windings. Primary winding has a tapping point for connection (N_p: primary winding; N_1+N_2), (N_s: secondary winding). Magnetizing inductance of flyback transformer is denoted by L_m. Converter has standard input EMI filter and rectifier circuit, also a bulk capacitor (C_b) is used to store energy in the primary side. Another circuit component is the boost inductor (L_b) which used directly to the positive input of the flyback transformer. Secondary side of the converter is similar to a standard flyback converter with output diode (D_o), output capacitor (C_o). PWM converter is a significant IC from *On semiconductor*, *NCP1207*. This IC provides Quasi-resonant mode of operation and works with free-running frequency. Converters dc-dc stage has to operate in BCM mode, and the boost inductor member has to operate in DCM mode of operation, in order converter to work in proper conditions.

Researchers put forward that the converter reaches low line-current harmonics that the converter will be sufficient for IEC 61000-3-2 Class 3 limits for lighting equipments. However, converter has problems of high bulk voltage and zero current distortion of input current. Researchers improve the converter and optimize the characteristic values with different experiments. Researchers determine the ratio of boost inductor to magnetizing inductor of transformer and the winding ratios of flyback transformer for optimized operation.

5.2.2 Converter Operation Mechanism

Converter operation system has five modes for one switching cycle. Three of the modes are the similar modes as standard flyback converter, but other two modes are the particular modes of this converter. Input voltage (v_{in}) of the converter is sinusoidal line voltage which is shown in (5.1) with RMS value (V) and angular line frequency (ω). It is assumed as constant during the switching cycle. In the equations V_b denotes bulk capacitor voltage, D denotes duty cycle of gate drive signal, T_s denotes switching cycle period, V_o denotes converter output voltage and L_m denotes magnetizing inductance of transformer.

$$v_{in}(t) = \sqrt{2}V \sin \omega t \tag{5.1}$$

a) Mode 1: Switch on, Diode reverse biased, time interval T_a - T_b

First mode starts when switch moves to on position at $t = T_a$. This operation results as reverse bias of the output diode. Current flows through the primary winding of flyback transformer, which magnetizes the transformer. On the secondary side, no current flows through because of the reverse biased diode. Output capacitor feeds the output load, LEDs. Equation 5.2 shows the magnetizing current (i_m), which is the sum of the C_b current (i_{cb}) and the L_b current (i_{lb}).

$$i_m = i_{cb} + \frac{N_1}{N_2} i_{lb} \tag{5.2}$$

Equation 5.3 shows the change in the current, i_m, which is denoted by Δi_m. The peak value of the boost inductor current ($i_{m,p}$) is equal to Δi_m. This is because of the DCM operation of the converter.

$$\Delta i_m = \frac{V_b}{L_m} \tag{5.3}$$

Current Δi_{LB} increases linearly with respect to voltage over it, and it works in DCM mode;

$$\Delta i_{LB} = \frac{v_{in} - (\frac{N_1}{N_p}) V_b \;\; DT_s}{L_b} \tag{5.4}$$

The flyback transformer magnetizing current is formed by bulk capacitor current and boost inductor current. This mode ends with changing the position of the switch to off state.

b) Mode 2: switch off, diode off, time interval T_b-T_c

Switch is in off position at the $t = T_b$. This mode has a short time interval with respect to other modes and continues until the output capacitance (C_{oss}) of the switch is charged. The voltage of this capacitor (V_{Coss}) reaches up to a value at the end of the mode;

$$V_{Coss} = V_b + \frac{N_p}{N_s} V_o \tag{5.5}$$

In this mode the currents i_{lb} and i_{cb} still continue to flow in the same direction, and flyback transformer continues to store energy.

c) Mode 3: switch off, diode on, time interval T_c-T_d,

This mode starts when the MOSFET oscillating capacitor reaches the value calculated in (5.5). D_o conducts and transformer releases the stored energy to the secondary side. The current, i_{lb}; decreases with respect to circuit composed of L_b and C_b. This mode continues until the energy on L_b is fully released. Equation 5.6 shows, the change of the boost inductor current:

$$\frac{di_{lb}}{dt} = -\frac{V_b + V_o \;\; N_2 \;\; N_s \;\; - v_{in}}{L_b} \tag{5.6}$$

This mode is different from the standard modes of flyback converters. Even if, the flux on the transformer turns in the opposite direction, the current in the primary side continues to flow. The equation 5.7 show the current i_m that continues to flow where i_s denotes output diode's current.

$$i_m = \frac{N_s i_s - N_2 i_{cb}}{N_p} \tag{5.7}$$

The formed circuit of L_b and C_b, do charges the capacitor by the input current. This makes the current i_{lb} and i_{cb} equal. This type of arrangement maintains the transfer of energy directly from the line to the load. Direct energy transfer increases the efficiency of the converter. The transferred energy, reflected to the secondary side can be shown by the secondary current value.

$$i_s = \frac{N_p}{N_s} i_m + \frac{N_2}{N_s} i_{lb} \tag{5.8}$$

The equation 5.8 illustrates the secondary side current, which involves magnetizing current and boost inductor current. Here, the key is; the boost inductor current equals to input line current.

d) Mode 4: switch off, diode on, time interval T_d - T_e ,

This mode starts at time $t = T_d$, which the current i_{lb} falls to zero. The boost inductor operates in DCM mode. Therefore, current flows in the primary side stops and transformer's energy continue to deliver to the secondary side.

e) Mode 5: Switch off, Diode off, time interval T_e - T_f,

This mode starts at the time $t = T_e$, when transformer totally demagnetizes. Therefore, the value of magnetizing current falls to zero. The circuit components, C_{oss}, L_m and C_b, form a resonant circuit. This operation provides, voltage fall on the switch to V_b-nV_o. The advantages of this operation will be detailed in other sections.

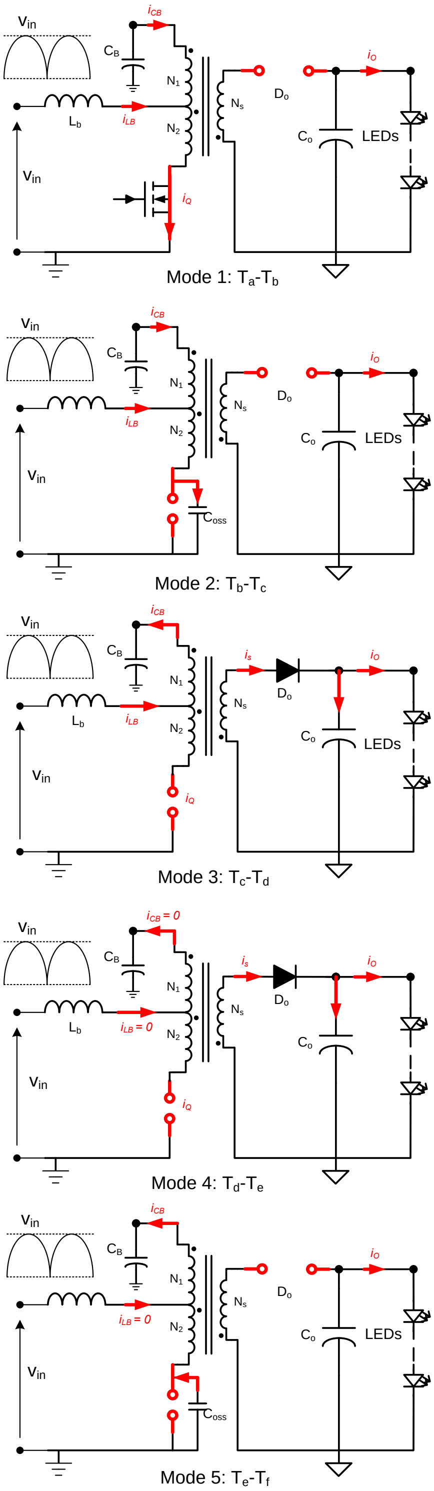


Figure 5.3 Operation modes for one switching period

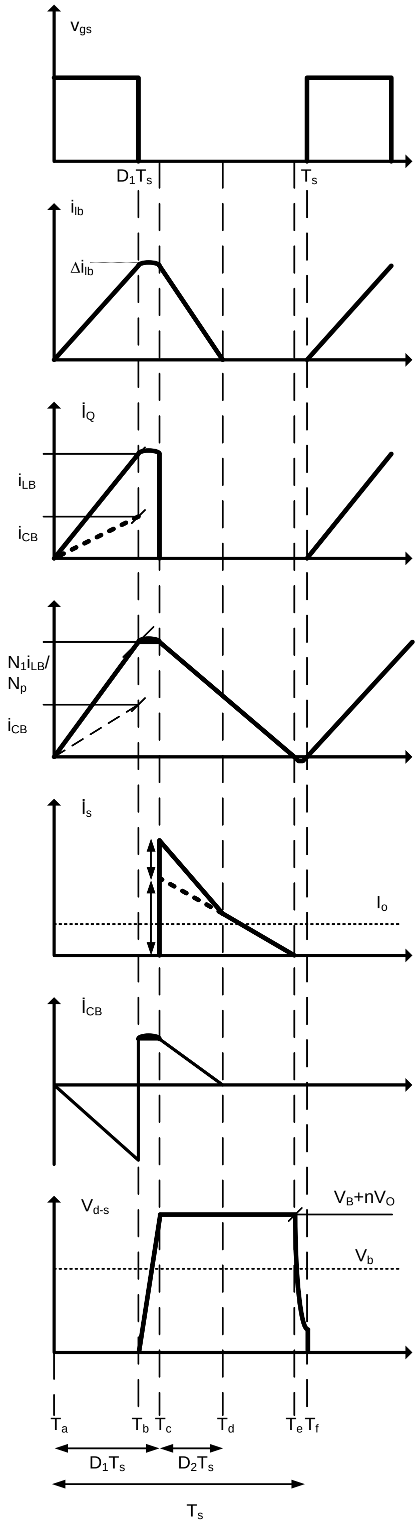


Figure 5.4 Characteristic waveforms for one switching period

The equations (5.9) and (5.10) shows the equations used in figures and further calculations. Here n denotes transformer transfer ration and V_{n1} denotes voltage on first part of primary winding of transformer.

$$n = \frac{N_p}{N_s} \tag{5.9}$$

$$V_{n1} = \frac{N_1}{N_p} V_b \tag{5.10}$$

5.3 Design of Single-Stage AC-DC Flyback Converter

This section introduces the design of the proposed flyback converter. The previous section defined the characteristic waveforms of the converter. First part of this section is the operation conditions of converter. Next part introduces the details of the converter and calculation of the converter parameters. Final section covers the design steps of the flyback converter, including passive and active elements.

5.3.1 Converter Operation Calculations

This section introduces the calculation of the converter's operation calculations proper to [26]. The converter has to operate in borderline conduction mode (BCM), and the boost inductor has to operate in DCM mode. These operation modes will guarantee the correct operation of converter with high efficiency and high power factor. The calculations are developed from the paper [26].

First calculation is the term for non-zero input line current. As it mentioned, input line current flows when the input line voltage is higher than the voltage on the primary winding, N_1, of the flyback transformer.

The figure 5.5 demonstrates the input current flow with respect to voltage, Vn1. At time intervals, $t = 0\text{-}t_1$ and $t = t_2\text{-}t_3$, current doesn't flow because line voltage is lower than a specific value. Current flows between interval $t = t_1$-t_2. The following equations show the calculations of these time intervals where T_{line} denotes time period of AC line.

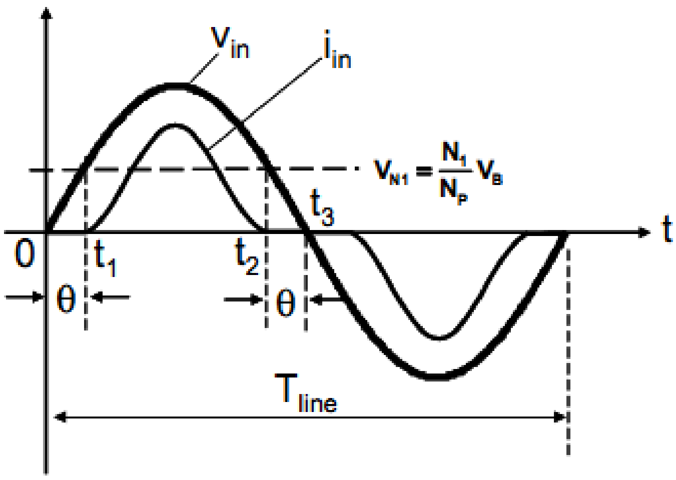


Figure 5.5 Characteristic waveforms of flyback converter, input voltage and input current [26]

$$t_1 = \frac{\sin^{-1}\left(v_{n1} \;\; \sqrt{2}v_{in}\right)}{2\pi} T_{line} \tag{5.11}$$

$$t_2 = \frac{T_{line}}{2} - t_1 \tag{5.12}$$

$$t_3 = \frac{T_{line}}{2} \tag{5.13}$$

First calculation for the characteristic functions of the converter is the duty cycle of switch. Equation 5.14 shows the duty cycle with respect to input and output voltage relation. The concept of voltage balance is used to calculate duty cycle as mentioned in previous sections. Duty cycle of switch signal (D_1) refers to the time interval T_0 to T_1. In the equations, T_s denotes one period of switching cycle, Δi_{lb} denotes change in boost inductor current.

$$D_1 = \frac{nV_o}{V_b + nV_o} \tag{5.14}$$

$$\Delta i_{lb} = \left(v_{in} - \frac{N_1}{N_p} V_b\right) D_1 T_s \,/\, L_b \tag{5.15}$$

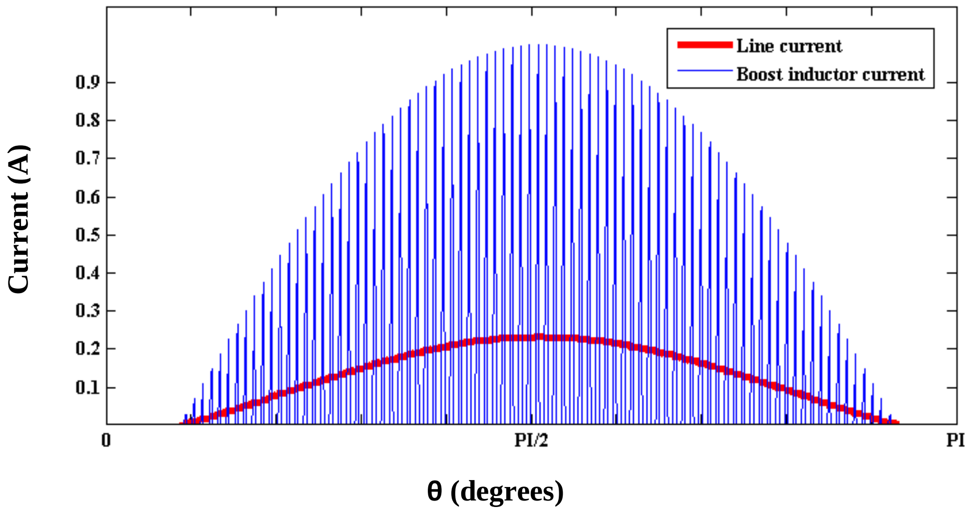


Figure 5.6 Converter characteristic functions, boost inductor current (blue) and line current (red)

Input line current equals to the boost inductor's current, i_{LB} and the change of the current defines the peak value of input current. The boost inductor must operate in DCM mode and demagnetize at every cycle. Equation 5.17 calculates the time interval for demagnetization of boost inductor, T_2-T_3, duty cycle (D_2), by the voltage-second law.

$$T_2 - T_3 = D_2 T_s \tag{5.16}$$

$$D_2 = \frac{(v_{in}\ t\ - v_{N1})D_1}{V_b + \frac{N_2}{N_s}V_o - v_{in}(t)} \tag{5.17}$$

The change of secondary current has two components as observed from the characteristic waveforms. The change of the waveform lasts for the time interval, T_b-T_d. Equation 5.18 involves the first portion of the secondary diode's current (Δi_{s1}) as;

$$\Delta i_{s1} = \quad n\Delta i_m + \frac{N_2}{N_s}\Delta i_{lb} \ \ |\,_{T_c}^{T_d} \ = \frac{n^2 V_O}{L_m} D_2 T_s + (N_2 \ \ N_s)\Delta i_{lb} \tag{5.18}$$

Equation 5.19 indicates the second part of the secondary current;

$$\Delta i_{s2} = \quad n\Delta i_M \mid_{T_d}^{T_s} \; = \frac{n^2 V_O}{L_M} (1 - D_1 - D_2)T_s \tag{5.19}$$

Equation 5.20 indicates the output current (I_o) which is the average value of the secondary current within a switching cycle,

$$I_o = \frac{1}{2} \Delta i_{s1} D_2 + \frac{1}{2} \Delta i_{s2} (D_2 + \; 1 - D_1 \;) \tag{5.20}$$

Another main characteristic function of the converter is the switching cycle (T_s). Researchers state that the combination of the previous functions will define the switching frequency (f_s) of the converter. In design steps, the switching frequency will selected and the other functions will be calculated with respect to it. The equation 5.21 shows T_s;

$$T_s = \frac{2I_o}{\frac{n^2 V_o}{L_m} D_2 + \frac{(N_2 \; N_S) \; v_{in}(t) - n_1 V_b \; D_1}{L_b} \; D_2 + \frac{n^2 V_o}{L_m} (\; 1 - D_1 \; ^2 - D_2^2)} \tag{5.21}$$

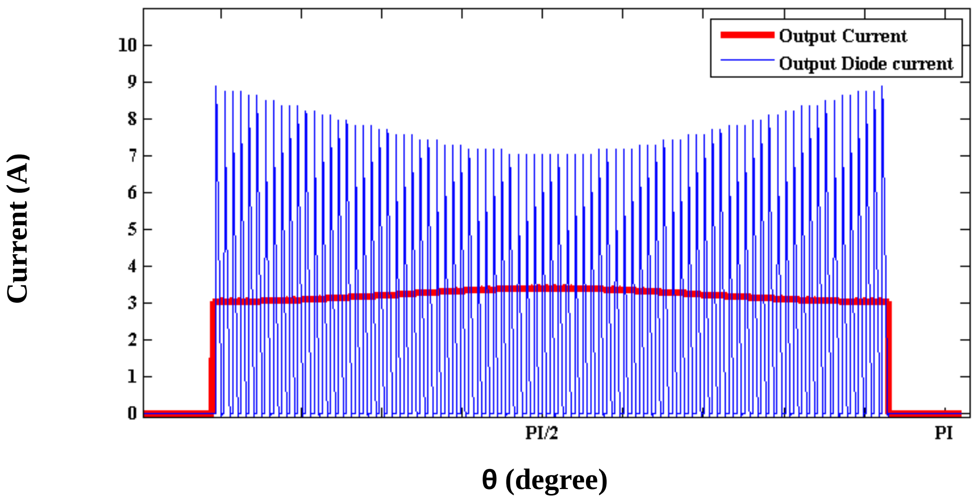


Figure 5.7 Converter characteristic functions, secondary diode current (blue), average output current (red)

Next equation 5.22 shows the boost inductor current (i_{lb}) which is also the input line current.

$$i_{lb} = \frac{1}{2} \Delta i_{lb} \;\; D_1 + D_2 \;\; = \frac{1}{2L_b} (v_{in}(t) - V_{n1}) D_1 (D_1 + D_2) T_s \tag{5.22}$$

5.3.2 AC-DC Flyback Converter Specifications

This section covers converter specifications and features of proposed converter [26]. Converter operates both at low and high line voltages. In order to operate in correct operation mode in both line voltages, circuit parameters have to be re-defined. The load is PLEDS, formed as four branches operating total of 24V and 3.25 A. Each branch contains seven LEDs in series.

Table 5.1 Converter characteristic parameters

Feature	Parameter
Input Line Voltage	110 V
Input Line Frequency	50 – 60 Hz
Input Current Ripple	20%
LED Load	28 HB-LED
LED Voltage	24 V
LED Current	3.25 A
Efficiency	> %80
LED Current ripple	< 10%
LED Voltage ripple	< 5%
Power Factor	> 0.90
Switching Frequency	100 kHz
Operation Mode	BCM/DCM
PWM controller	NCP1207

5.3.3 Converter Circuit Parameter Calculations

This part introduces calculation of the circuit parameters. There are several suggestions to design of flyback converter. However, the proposed converter is distinctive from standard AC-DC flyback converters and single-stage flyback converters. Therefore, the design steps will be different from the usual designs. This part includes calculation and choice of components of the proposed converter. Researchers define the converter's characteristic elements like boost inductor and magnetizing inductance. In order to design the converter, these parameters are the key values;

Table 5.2 Flyback converter key parameters

Component	Symbol	Parameter
Magnetizing Inductor	L_m	640uH
Boost Inductor	L_b	160uH
Bulk Capacitor	C_b	120uF / 420V
Output Capacitor	C_o	2x1000uF / 25 V
MOSFET	Q_1	SPP15N65C3
Output Diode	D_o	STPS20H100CT

Researchers defined the converter passive elements; however in this section these parameters will be evaluated.

One of the variables is the minimum value of the DC link capacitor voltage (V_{DC}^{min}). The calculation of the capacitor of proposed converter is a complex calculation, in the research the bulk capacitor voltage is measured for different voltage parameters. DC link voltage is calculated in order to obtain the converter parameters. In the equations, V_{line}, min value defines the minimum voltage of the line, D_{ch} is the charge time of the capacitor which is taken as 0.2, f_L is the line frequency.

5.3.3.1 Step 1: Input power calculation

From the converter characteristic parameters, input power can be calculated in order to use in further calculations. In the equation *Eff* denotes the efficiency, P_o is output power and P_{in} is input power.

$$P_{in} = \frac{P_o}{Eff} = 97.5\ W \tag{5.23}$$

5.3.3.2 Step 2: Rectifier output voltage rating calculation

$$V_{DC}^{min} = \sqrt{2\left(V_{line}^{min}\right)^2 - \frac{P_{in}(1 - D_{ch})}{C_{dc}f_L}} = 45\,V \tag{5.24}$$

The minimum voltage is calculated by taking the link capacitor (C_{dc}) value as 120 uF. This variable will be used to calculate the magnetizing inductance value of the transformer. Another parameter is the maximum voltage value (V_{DC}^{max}) which is calculated for low line voltage by using the maximum value of input line voltage (V_{line}^{max});

$$V_{DC}^{max} = \sqrt{2V_{line}^{max}} = 225\,V. \tag{5.25}$$

5.3.3.3 Step 3: Switching frequency and duty cycle calculation

The converter operates in free-running frequency mode of operation, which means frequency changes during the converter operation with respect to input and output conditions. Designer has to select the frequency at a given operating point.

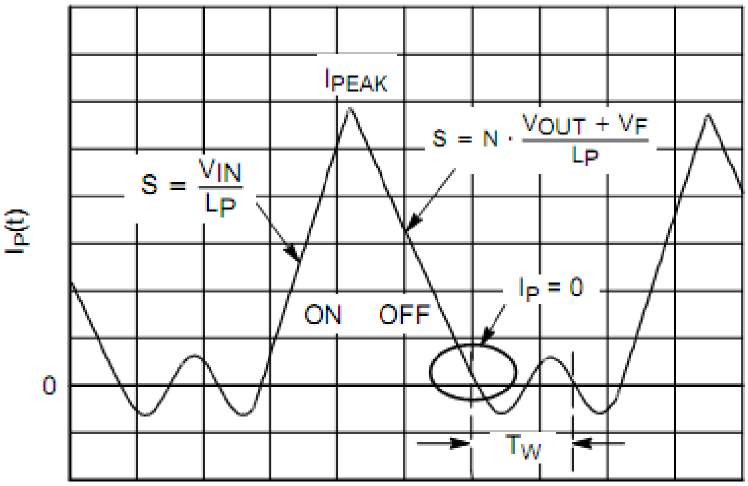


Figure 5.8 Primary inductor current illustration of flyback converter [36]

In the standard converters, switching frequency is calculated by calculating the time intervals of switching period. These intervals change with the input and output parameters like the Figure 5.8.

However, the proposed converter has a different type of operation. There are mainly two parameters that affect the operation of the converter, first is the ratio of boost inductor to magnetizing inductor and the second is the ratio of the windings of the converter. The following equations define these variables;

$$\alpha = \frac{L_b}{L_m} \tag{5.26}$$

$$n_1 = \frac{N_1}{N_p} \tag{5.27}$$

Therefore, the different structure of the converter introduces a complex calculation of the switching frequency, which equation 5.20 details the calculation.

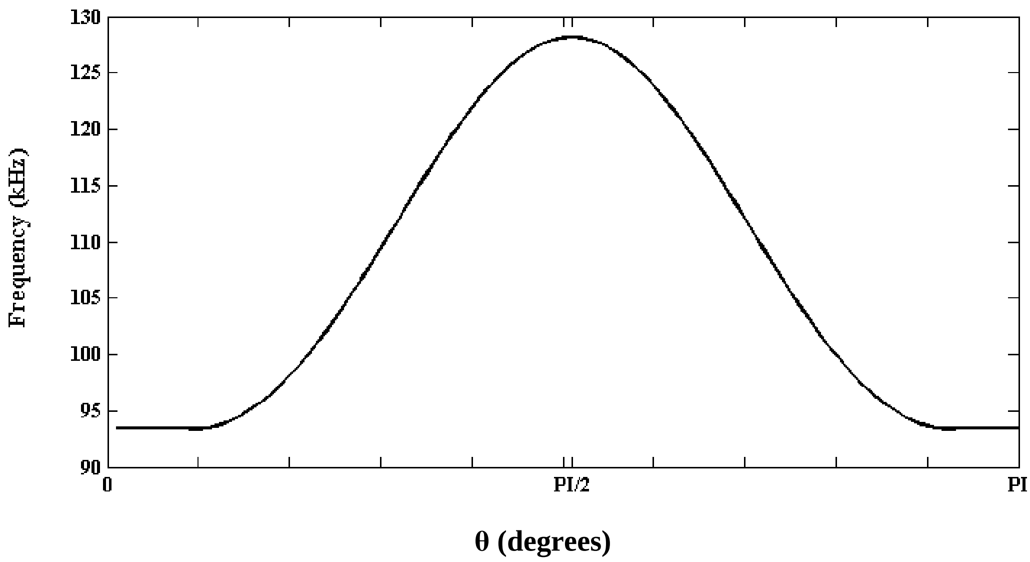


Figure 5.9 Converter operation frequency with respect to time

Equation 5.14 calculates D1 as;

$$D1 = 0.32 \tag{5.28}$$

D2 value is not constant and changes with respect to input voltage and represented as;

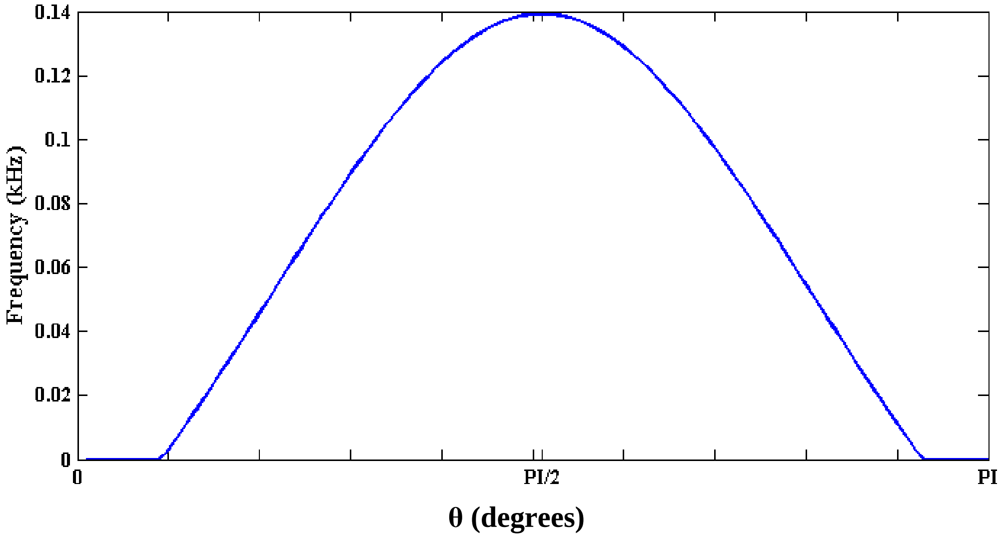


Figure 5.10 Converter characteristic functions, duty cycle D2(t)

5.3.3.4 Step 4: Transformer Design

Transformer design is the key design of flyback converters. Transformer can be manufactured easily with basic calculations and practical experience. However, the core selection, the wire type, the winding technique and gap length are some of design parameters of transformer. This part introduces the design steps of flyback transformer. Researchers introduce the key parameters of the flyback transformer, since it is the main part of the design. In addition the flyback transformer is unique for the proposed converter with three windings. The primary winding is a single wire but has a tapping location, the secondary winding is for the output part, and third winding is the auxiliary winding.

Researchers define the transformer parameters and magnetizing inductance. Auxiliary winding is calculated with respect to over-voltage principle of the PWM controller. First of all the minimum value of magnetizing inductance ($L_{m,min}$) calculation will be reevaluated with (5.10).

Table 5.3 Flyback transformer details

Feature	Parameter	Unit
Core Type	PJ33/19	Core
Primary Winding	30	turn
Primary Cable	Φ0.55	mm
Primary Winding Part1	4	Turn
Primary Winding Part2	26	Turn
Secondary Winding	5	Turn
Secondary Cable	Φ0.55	Twisted, mm
Magnetizing Inductance	650	uH
Auxiliary Winding	3	Turn
Auxiliary Winding Cable	Φ0.1	mm

$$L_{m,min} = \frac{(V_{DC}^{min} D_{max})^2}{2P_{in} f_s K_{RF}} = 100\, uH \tag{5.29}$$

In the equation, D_{max} denotes the maximum duty cycle value. The duty cycle is constant during the operation, which is selected as 0.32 in the previous section. The other variable, f_s is the switching frequency, 100 kHz, and K_{RF} denotes the ripple factor in full-load condition. This variable is defined as 1 for DCM mode of operation and defined as <1 for CCM mode of operation.

Magnetizing inductance is calculated to be 100 uH, for minimum value, however defined value for the magnetizing inductance is 650 uH. Therefore further parameters will be calculated with this inductance value.

Next design parameter is the transformer core definition; the methodology of transformer design suggests choosing the transformer core for the first step. Researchers select a proper core, but the other details are not defined. Therefore, the design steps will be developed with a co-work with given values.

The main parameters, the magnetizing inductance and output power define the type of the core. Manufacturers provide tables, to select the core type with respect to the power rating. Researchers selected PJ33/19 and table 4.3 involves the details of this core.

Table 5.4 PJ33/19 Core parameters

Parameter	**Symbol**	**Value**	**Unit**
Core factor	$l\ A$	0.331	mm^{-1}
Effective Volume	V_e	9440	mm^3
Effective Length	I_e	55.9	mm
Effective Area	A_e	169	mm^2
Minimum Area	A_{min}	142	mm^2
Mass of Set	m	≈ 43	g

Researchers developed the turn ratios and wire size of the flyback transformer. In order to develop the design steps, the calculations will be evaluated in this part. First, minimum turn-ratio of the primary side (N_p^{min}) is calculated. Equation 5.25 L_m denotes magnetizing inductance, I_p denotes peak current of magnetizing inductance, A_e denotes the cross-sectional area of core and B_{sat} denotes saturation flux density as shown in table 5.4. As a rule of thumb, for ferrite materials, designers use B_{sat} = 0.3~0.35 Tesla. Minimum primary winding (N_p^{min}) is calculated to be;

$$N_p^{min} = \frac{L_m I_p}{B_{sat} A_e} \times 10^6 \quad turns \quad = 26\ turns \tag{5.30}$$

Researchers select the primary winding as 30. Next step is to calculate the reflected voltage from secondary side to the primary side (V_{ro}) in order to calculate the minimum value of turn ratio of transformer (n_{min}).

$$V_{ro} = \frac{D_{max}}{1 - D_{max}} V_{DC}^{min} = 70.5\ V \tag{5.31}$$

$$n_{min} = \frac{N_p}{N_s} = \frac{V_{ro}}{V_o} = 4 \tag{5.32}$$

The minimum turn ratio is calculated to be 4, and researchers define turn-ratio as 6. Final winding of the converter is the auxiliary winding of the transformer. The IC feeds directly from the high line voltage; this pin ensures the over-voltage protection. This voltage level is defined as V_{cc} = 7.2 V. The auxiliary winding (N_a) is calculated by following equation;

$$N_a = \frac{V_{cc}}{V_o} N_s = 3\ turns \tag{5.33}$$

Next calculation is the gap length (l_g) of the transformer with (5.34). Here the essential value is AL which is specific for transformer core material and defined by core manufacturer. AL-value has unit of nH/turns^2. This variable is calculated to be;

$$l_g = 40\pi A_e \quad \frac{N_p^2}{1000L_m} - \frac{1}{AL} \quad = 120\ um \tag{5.34}$$

Final calculation for the transformer is the wire diameter calculation for each winding. This calculation is based on the RMS current values of each winding. The current density of typical copper wires are 6-10 A/mm^2. As the wire diameter increases the resistance value decreases and the loss on the wire decreases, however eddy current losses increase. It is recommended to use parallel windings with multiple strands of thinner wires. This configuration minimizes the skin effects.

5.3.3.5 Step 5: Snubber Design

Snubber circuit absorbs the current in the leakage inductor of the transformer and used to protect the over-voltage over the MOSFET drain caused by the leakage of the inductor. Otherwise when the MOSFET is turned off, high voltage spike causes the MOSFET and the PWM converter to damage.

There are various circuits for snubber application; here RCD snubber circuit will be designed at full-load condition. In the calculation main parameters are minimum voltage over snubber circuit value (V_{sn}) and power dissipation of the snubber circuit (P_{sn}).

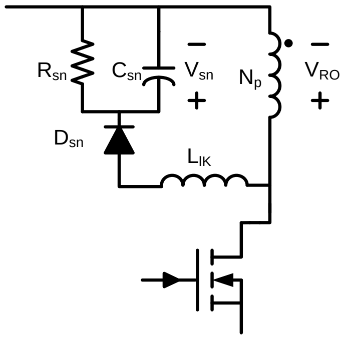


Figure 5.11 RCD snubber circuit layout

The peak current value of MOSFET (I_{ds}^{peak}) is calculated by MATLAB function developed in previous section, L_{lk} denotes the leakage inductance of the primary inductor (can be defined as ten percent of magnetizing inductance or measured by the primary windings while the other windings are short circuited). V_{sn} is defined as 2~2.5 times of the V_{ro}. R_{sn} denotes the snubber resistance and C_{sn} denotes snubber capacitance.

$$P_{sn} = \frac{(V_{sn})^2}{R_{sn}} = \frac{1}{2} f_s L_{lk} (I_{ds}^{peak})^2 \frac{V_{sn}}{V_{sn}-V_{ro}} = 2\ W \tag{5.35}$$

$$R_{sn} = 1.15\ k\Omega \tag{5.36}$$

The snubber capacitance (C_{sn}) is calculated with respect to the voltage ripple on the capacitor (ΔV_{sn}). The ripple on the capacitor of the snubber is defined as five to ten percent of nominal voltage.

$$C_{sn} = \frac{V_{sn}}{\Delta V_{sn} R_{sn} f_s} = 8.7\ nF \tag{5.37}$$

5.3.3.6 Step 6: Active Components Selection

5.3.3.6.1 NCP1207, PWM Controller

NCP 1207 is a current mode PWM controller for free-running frequency, manufactured by *On Semiconductor*. NCP1207 involves several features; borderline operation, over voltage protection, demagnetization detection, dynamic-self supply, free-running frequency operation, skip cycle operation and over current detection. These features are significant for the true operation of proposed flyback converter. This section details the features and internal architecture of NCP1207.

Borderline operation is performed with transformer reset detection property of the controller. Borderline operation of flyback transformer causes, transformer to work between CCM and DCM mode. NCP1207 watches the voltage of transformer primary winding with auxiliary winding by *DEMAG* pin. Here, are two operations; first is over-voltage detection. If the voltage exceeds 7 V, controller stops the operation. Second is demagnetization detection; the figure 5.12 displays *DEMAG* signal. In this signal, each point crossing zero is a possible restart operation for the controller. This operation eases the feedback circuitry of the converter and helps to switch in the low voltages. Switching at low voltage reduces the power loss of the converter.

NCP1207 is a developed PWM controller that operates in quasi-resonance operation. The *DEMAG* signal is also used for quasi-resonance operation. The demag signal is similar to MOSFET signal, so the valley points of the D-S voltage of MOSFET is equal to *DEMAG* signals zero crossing points. If the switching occurs at these points, the switching voltage will be extremely low. This feature reduces the stress on the MOSFET and noise of the converter.

NCP1207 performs dynamic-self supply operation. This operation is the supply system of controller directly from the high voltage input. This technology ensures a charge up circuitry and provides 12 V at V_{cc} pin of the controller. NCP1207 has a unique property of skipping cycles. The skip capability is a choice of designer that the controller does not work at low power with respect to rated power of the controller. This mode of operation is also named as Burst mode, which increases the efficiency at light loads.

The controller ensures free-running frequency. Free-running frequency operation eases the control of the converter and the base principle for a single-stage flyback converter. Designer limits the highest level of operating frequency. During the operation, the controller changes the frequency with respect to loading and input voltage characteristics.

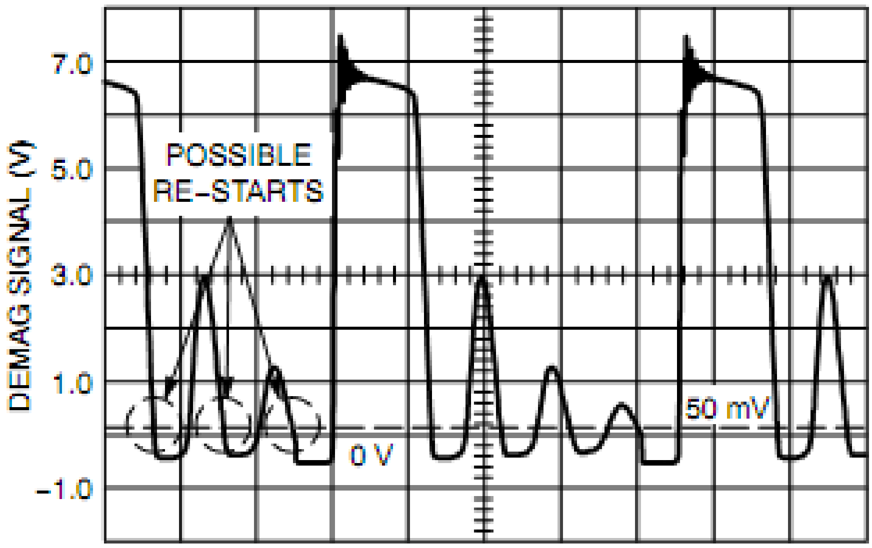


Figure 5.12 Demagnetization signal of flyback transformer [36]

The control part of the controller is *FB* and *CS* pin which are crucial for converter operation. *FB* pin watches the signal applied from the secondary side by an *opto-coupler*. Feedback voltage shows the loading condition, if the load increases feedback voltage increases. *FB* pin sets the limit point for the primary peak current. Another feature of this pin is the over-current detection. There is a maximum voltage limit on this pin, and if it is exceeded the controller stops the operation. The soft-start operation follows this failure that, in every 1 ms, controller pulls the output to high and control the pins. In addition, if the opto-coupler wrecks or output is lost, again the controller stops the operation.

CS pin watches the MOSFET current with a current sense resistor. Designer selects the upper limit of the MOSFET current, which defines the resistor value connected to the *CS* pin. Controller compares the voltage on *CS* pin and *FB* pin with an internal op-amp. Basically if, the voltage on the *CS* pin is lower than *FB* pin voltage, drive circuit is settled to work. Else the controller stops operation. Another property is skipping cycle; a resistor connected to *CS* pin defines the level of skipping.

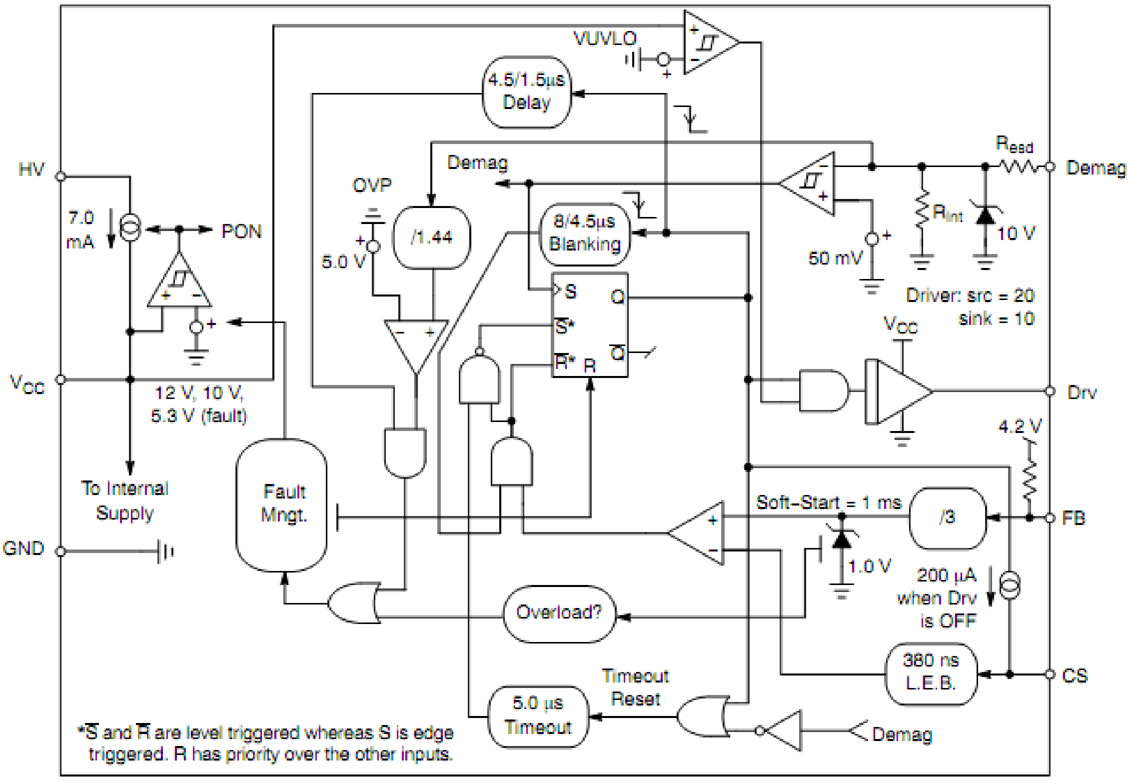


Figure 5.13 NCP 1207 controller internal structure

5.3.3.6.2 MOSFET Selection

This part involves the MOSFET selection within a systematical process. This part involves the calculation steps. First step is to calculate the maximum voltage on the MOSFET during the converter operation. This will define the maximum D-S voltage ($V_{ds\text{-}max}$) of the MOSFET. The maximum voltage occurs at the highest input value ($V_{in\text{-}max}$) and calculated by;

$$V_{ds-max} = V_{in-max} + nV_o = 350\,V \tag{5.38}$$

The voltage on drain-source changes with respect to the change in the input voltage waveform. Therefore, choosing a MOSFET with a rating of 600 V will be a reasonable choice. Second step is to calculate the current ratings of the MOSFET. The drain current of the MOSFET in this converter is not continuous, which has duration as on-time of the switching period. The equation 5.27 introduces the MOSFET current (i_m);

$$i_m = i_{cb} + \frac{N_1}{N_p} i_{lb} \tag{5.39}$$

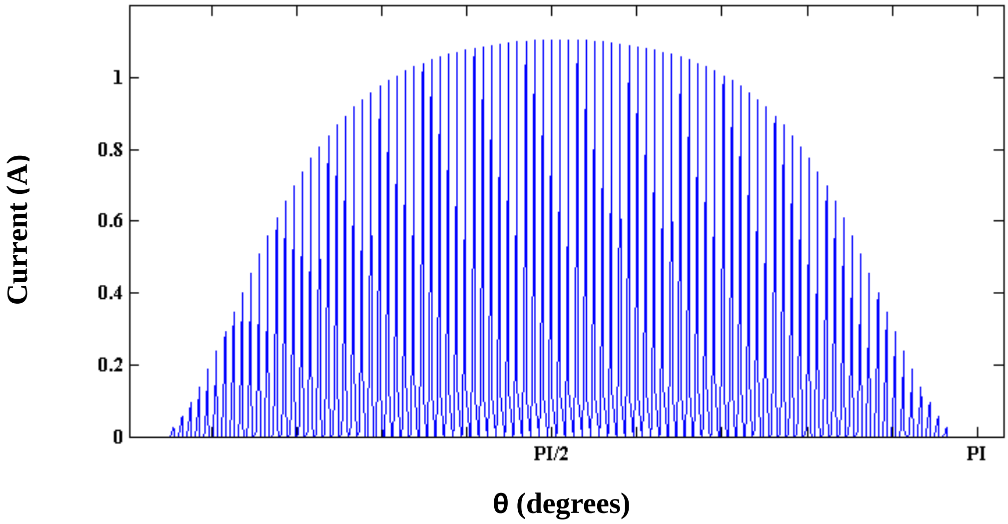


Figure 5.14 Converter characteristic function; MOSFET current

Here, MOSFET current changes with respect to input voltage, transformer winding ratio, boost inductance and magnetizing inductance. The equations show the peak value of i_m (I_{m-peak}) and RMS value of i_m (I_{m-rms}).

$$I_{m-peak} = 1.1\ Amps \tag{5.40}$$

$$I_{m-rms} = 0.272\ Amps \tag{5.41}$$

Next step is defining the gate charge value of the MOSFET. The gate charge (Q) can be calculated (5.28) where I_{out} denotes the PWM controller drive current.

$$Q = \frac{2 * I_{OUT}}{f_s} = 75\ nC \tag{5.42}$$

Final step is to calculate the power dissipation of the MOSFET. In order to calculate the power dissipation, the MOSFET has to be selected. The previous calculations; defines the basic parameters of MOSFET. In addition, there are various types of MOSFET that provides these properties. If designer use a MOSFET with low $R_{DS\text{-}ON}$ value, the dissipation will decrease. However, the cost of the MOSFET will increase. At this point, it is the choice of designer to use high price device or use a low price device with brings another component to transfer the heat, heat-sink.

Researchers chose the MOSFET as SPP15N65C3 (Cool MOS Power Transistor) from *Infineon Technologies* company. Device is available as dip package TO220-3-1. Table 5.5 defines the properties of MOSFET.

Table 5.5 MOSFET properties, SPP15N65C3

Property	**Symbol**	**Value**	**Unit**
Drain-Source Breakdown Voltage	$V_{BR(DSS)}$	650	V
Drain-Source On Resistance	$R_{DS(on)}$	0.28	Ohm
Continuous Drain Current	I_D	15	A
Gate Charge Total	Q_G	63	nC
Thermal Resistance (junction to case)	R_{thJC}	0.8	K/W
Thermal Resistance (junction to ambient)	R_{thJA}	62	K/W
Total Power Dissipation	P_{tot}	150	W

The RMS value of the MOSFET current, $I_{q\text{-}rms}$ is calculated by using MATLAB. At each switching cycle, the peak value and the duty cycle changes; therefore each switching cycle divided into 100 pieces also the one line period divided to 100 pieces. (MATLAB code is in the appendix C.2)

Equation 5.30 shows the power dissipation of MOSFET during conduction (P_{on});

$$P_{on} = I_{q-rms}^2 R_{DS(on)} = 1\ W \tag{5.43}$$

Second power loss is the switching power losses (P_{sw}), during turn-on and turn-off.

$$P_{sw} = \frac{1}{2} I_{q-rms} V_{DS} \; t_{on} + t_{off} \; f_s = 0.5\, W \tag{5.44}$$

Total loss of the MOSFET (P_D) is the sum of the (5.43) and (5.44) which is;

$$P_D = \quad 1.5\, Watts \tag{4.61}$$

Table 5.5 defines the properties of the MOSFET including allowed power dissipation and thermal resistance of junction to ambient (R_{thJA}). If MOSFET is used without heat-sink at ambient temperature (T_a) of 25°C, junction temperature (T_j) will be;

$$T_j = T_a + P_D R_{thJA} = 140°\mathrm{C} \tag{5.45}$$

Therefore, there must be a heat-sink in order to transfer the heat without harming the MOSFET. Here, maximum junction temperature (T_{jmax}) assumed as 115 °C maximum and heat-sink thermal resistance (R_{thh}) of the MOSFET is calculated by (5.46). In the equation MOSFET thermal resistance junction to case (R_{thjc}) is used for the calculation.

$$R_{thh} = \frac{T_{jmax} - T_a}{P_D} - R_{thjc} = 50\, K/W \tag{5.46}$$

5.3.3.6.3 Diode Selection

In the second mode of operation, the current flows from the diode with a similar waveform of MOSFET current. This part develops the selection method of diode. First step is to calculate the voltage and current ratings of the diode.

Equation 5.47 calculates the voltage rating of the diode (V_{d-max}):

$$V_{d-max} = V_o + nV_b = 75\, V \tag{5.47}$$

Second is the current rating of the diode; by using the same method for MOSFET's current calculation, diode current waveform is calculated by MATLAB. The RMS value of diode current is calculated as 2.2 A.

Researchers chose a schottky rectifier as "STPS20H100CT" from *"ST Microelectronics",* Table 5.6 defines the properties of the diode.

Table 5.6 STPS20H100CT Schottky rectifier features

Property	**Symbol**	**Value**	**Unit**
Maximum Peak Reverse voltage	V_{RRM}	100	V
Average Forward Current	I_{av}	2x10	A
Forward Voltage	V_f	0.56	A
Thermal Resistance (junction to case)	R_{thj-c}	3.2	K/W

Equation 5.48 calculates the loss of the diode (P_{diode}), by multiplying the forward voltage drop and average forward current.

$$P_{diode} = V_f I_{drms} = 1.24\ W \tag{5.48}$$

Equation 5.35 calculates the junction temperature, with respect to power dissipation and the thermal resistance value.

$$R_{thh} = \frac{T_{jmax} - T_a}{P_D} - R_{thj-c} = 60\ K/W \tag{5.49}$$

These components are the active elements of the converter. Designers choose the other passive elements like resistors with respect to the power ratings and the tolerance values.

Next section involves the converter simulation, in order to test the voltage and current ratings, converter working principle and converter input and output; voltage and current values investigation.

5.4 Implementation of Flyback Converter by Computer Simulations

In this chapter converter simulation will be performed by using program Simplorer v7.0 by *Ansoft*. Converter electronic components are the parts from the program's library. The active devices, MOSFET and diodes are defined with respect to their properties. The library does not contain the IC like the one used in Flyback converter. The program uses equation blocks in order to implement the features of PWM converter. The equation blocks constitute the internal structure of IC.

5.4.1 Simulation Application of Flyback Converter

This section details the simulation application of flyback converter. Simulation application involves the components selection, construction of circuit and building up the equation blocks. Most of the components are directly used from the elements of the simulation programs library, only for the active elements, the details of the element of the library is adapted to the used ones. Diode and MOSFETs values are changed with respect to the application. The circuit is constructed with respect to these models. First test of the constructed circuit is performed with a PWM module for MOSFET gate drive with constant frequency and constant on-time. Final construction of the simulation is setting up the equation blocks, in order to provide the proposed operation for the converter. Simulation program contains various control blocks for MOSFET gate drive. However proposed converter uses a particular IC, and the gate drive circuitry has to be developed specially. For this, equation blocks are preferred. The equation blocks are; PWM module, MOSFET peak current calculator, Quasi-resonance determination and MOSFET gate drive. MOSFET gate drive module has inputs from the other modules and determines the frequency of the drive signal and the duty cycle of the gate drive. PWM module delivers constant frequency PWM signal, MOSFET peak current calculator calculates the peak value of the MOSFET current so the magnetizing inductor current, by using the output voltage, output current, and input voltage values. Quasi-resonance module follows the MOSFET drain to source voltage values and gives information about the proper moment of switching action. These moments are the times where the D-S voltage value oscillates and has a low voltage values as valleys.

Figure 5.15 presents the simulation schematic and Table 5.7 details the simulation and converter parameters. Table 5.8 details the peak current values of the MOSFET for selected input voltage values. This table shows the values for maximum loading conditions.

Table 5.7 Flyback converter simulation parameters

Parameter Description	Abbreviation	Value	Unit
Simulation Maximum Step size	H_{max}	0.1	msec
Simulation Run Time	T_{end}	100	msec
Integration Formula		Trapezoidal	
Power Stage Parameters			
Input Line Voltage	$V_{in,rms}$	110-220	Vrms
Magnetizing Inductance	L_m	650	uH
Leakage Inductance	L_{leak}	10	uH
Boost Inductor	L_{boost}	145	uH
Bulk Capacitor	C_B	120	uF
Output Capacitor	C_o	3.3	uF
Snubber Capacitor	C_c	25	nF
Snubber Resistor	R_c	54	k Ω
Control Parameters			
Current Sense Resistor, MOSFET	R_s	0.1	Ω
Current Sense Resistor, LED	R_c	1	Ω

Table 5.8 Flyback converter, MOSFET peak currents with respect to input voltage

Input Voltage	Peak Current Value	Input Voltage	Peak Current Value
120	3,234	210	2,498
130	3,101	220	2,454
140	2,987	230	2,414
150	2,889	240	2,377
160	2,803	250	2,343
170	2,727	260	2,312
180	2,660	270	2,284
190	2,600	280	2,257
200	2,546	290	2,232
210	2,498	300	2,209

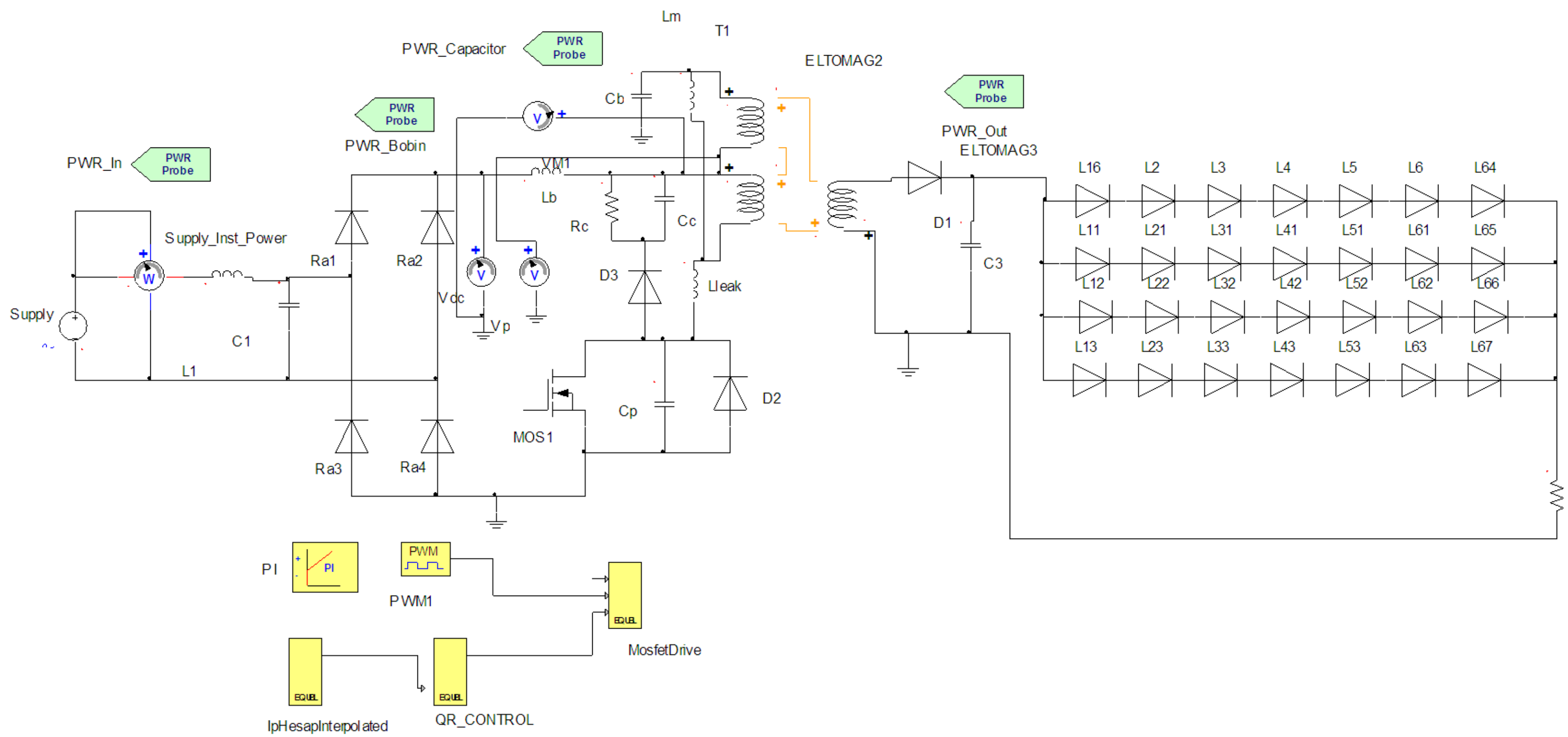


Figure 5.15 Flyback converter simulation application circuit layout

Another note is the load of the converter; first tests are performed with a resistor as a load. After improving the control system of the converter and idealizing the element values, LEDs are modeled as the loads. LED model is a diode with specific forward voltage drop and ESR value. Transformer of the converter has a different layout, which has no similar module in the component library of the simulation program. In order to find the correct model for transformer, different type of transformer modules are tested and best solution is found with magnetic parts.

Each part of the converter is tested as a single module and then it is integrated to converter. Also simulation is repeated for different component values several times in order to test the effect of the elements to the converter operation mechanism. Here the aim is to prove the circuit operation of the converter as the proposed converter.

5.4.2 Simulation Results of Flyback Converter

This part introduces the simulation results of the Flyback converter. The purpose of the simulation is to investigating the operation mechanism of the converter and confirming the resultant waveforms with the analytical calculations.

First of all it is expected that the converter will have high power factor and low harmonics at line current. Gate drive of the MOSFET will have a varying frequency and duty cycle of this signal will be adjusted for correct operation. Another action is the inductors working modes, which has a major role for correct operation of the converter. These are boost inductor which works in DCM mode of operation and magnetizing inductor of transformer which should work in BCM mode of operation. Figure 5.16 shows some of the characteristic waveforms of the converter; output diode current, MOSFET current and boost inductor current.

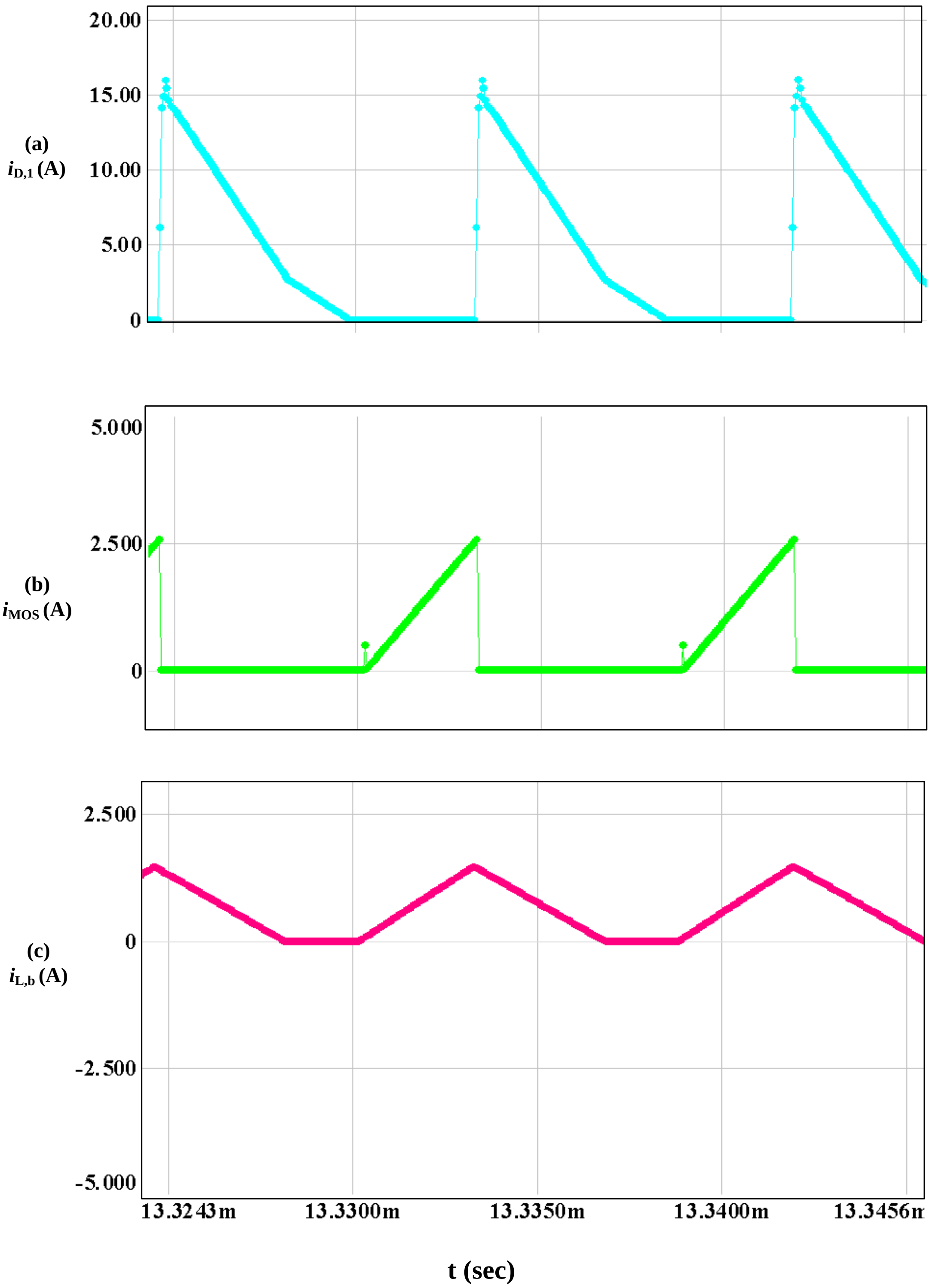


Figure 5.16 Flyback converter characteristic waveforms: (a) output diode current, (b) MOSFET current (c) boost inductor current

The figures confirm the proposed operation modes of the converter, and the analytical results computed by MATLAB. Therefore the peak and average values of the converter are same at analytical and simulation results. In order to obtain these results at simulation, each part of the simulation elements are tested specifically and all of the values are tested to confirm the correct operation. Other result of the simulation program is the output voltage and current waveforms of the converter. Figure 5.19 introduces the output characteristics of the converter.

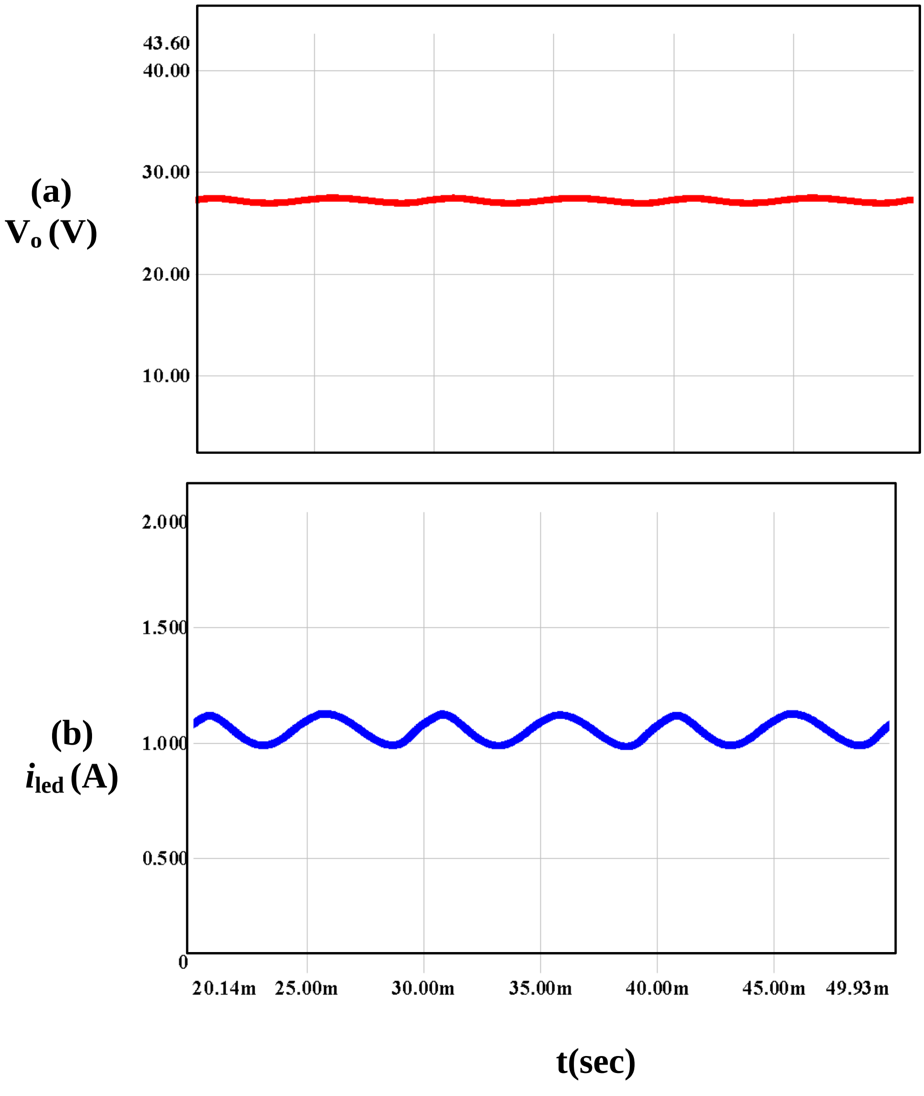


Figure 5.17 Flyback converter, (a) output voltage, (b) output current

These waveforms are obtained for different input voltage values and for different loading conditions. First of all the analytical calculations are confirmed with correct output voltage and current values. Then the control parameters are re-designed for correct operation in order to correct regulation of the output voltage and current.

The output average value is 25.2 Volts, and the branch of LED has an output of 1.1 Amps. The waveforms oscillate at twice of the line frequency.

Next figure displays the voltage waveform of the MOSFET, which peak value is about 750 Volts. The controller applies quasi-resonance operation which is proved that the switching occurs at a lower point. This point has a value of 33 Volts.

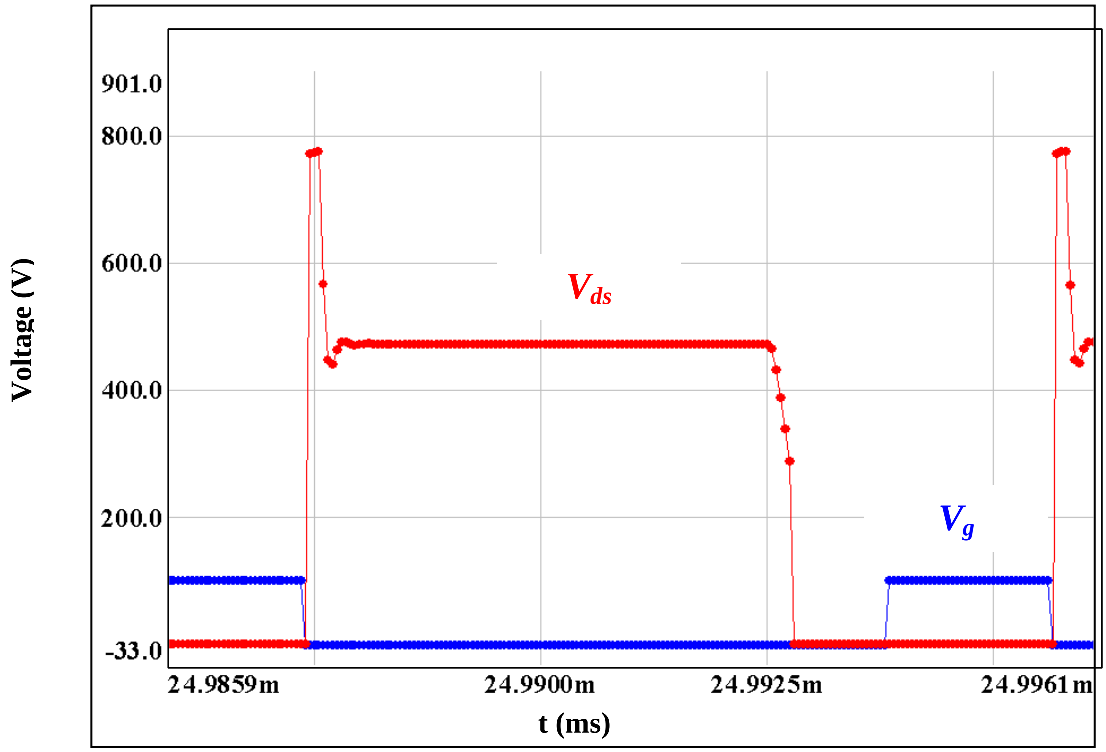


Figure 5.18 Flyback converter, MOSFET D-S voltage(red), gate drive (blue)

This D-S voltage (V_{ds}) waveform is a sample from any time of operation. This waveform shows the peak value of this waveform and the Quasi-resonance mode of operation with respect to gate voltage (V_g) of switch. Final waveform is the input voltage and current waveform which is shown in figure 5.19.

Input current value is non-zero in most of the part during the operation and follows the input voltage value, which improves the power factor of the converter. The analytical calculations show that the input current will flow when the voltage on the primary winding of the transformer is lower than the input line voltage. This can be observed from the figure that the input line current start to flow about 50 volts which is the voltage on the primary winding. Another point is input line current has a waveform nearly a sinusoidal and following the input line voltage. As a result of the simulations this type of configuration and control system proposes a high quality power converter.

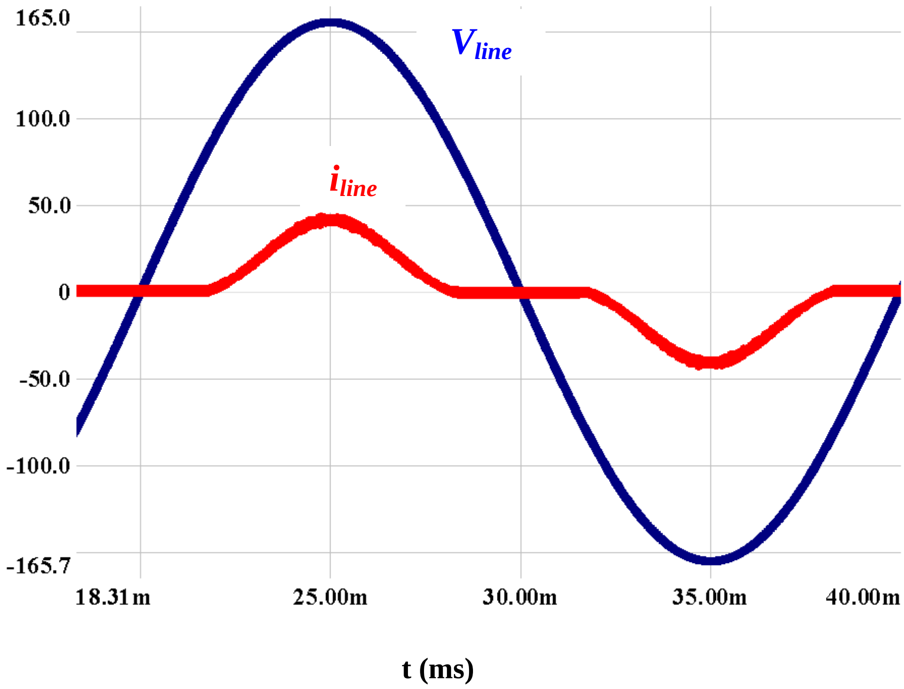


Figure 5.19 Flyback converter, input voltage (red), input current (green)

5.5 Manufacturing and Experimental Verification of the Flyback Converter

First part of this section covers manufacturing the flyback converter, by designing the printed circuit board and assembling the electronic components. Second part includes the experimental verification of the converter. Therefore, verification must include loading tests, input voltage tests and performance tests. Board design is a distinctive operation which affects the performance of the converter even the converter couldn't operate if the boar is improper. Board design includes component placement, track widths, length of the tracks. In this design, the method is, dividing the converter into parts as power conversion, IC, feedback, and supply parts. Each part is designed separately and integrated in one layer. Component are tried to assemble as close as possible, and the tracks that carry currents in two directions designed to be as short as possible. Also the ground connections are designed to be connected in one point. In addition to the components that are obligatory to converter to work, there are additional components like MOVs, filter components and Zener diodes protecting the circuit elements and improving the performance of the converter. Converter has to resist to failure conditions; short circuit situation, open circuit situation, input line voltage spikes.

5.5.1 Manufacturing the Flyback Converter

Manufacturing the converter involves different stages. The beginning point is the printed circuit board design of the converter by circuit programs as *Altium* Designer. *Altium* Designer, is a circuit design program, involves various features like schematic design, PCB design. The process on *Altium* design involves; defining all of the circuit elements in the library of the program, and drawing the circuit schematic with respect to design elements. Here, defining the elements is essential to have true shape on the PCB. Next stage is designing the PCB, by converting the schematic to a PCB. However, designer has to allocate the electronic components and define all of the parameters like, trace width, trace length, trace layer. PCB design is a detailed process and not the scope of this research. After, finishing the PCB design the board has to be manufactured by individual manufacturers. Designer defines the board type, board thickness, copper thickness on the board and color of the board. The table 5.10 details the board properties;

Table 5.9 Flyback converter PCB properties

Property	**Parameter**	**Unit**
Board Type	FR-4	Non-unit
Copper Thickness	70	um
Board Color	Green	Non-unit
Board thickness	1.6	mm

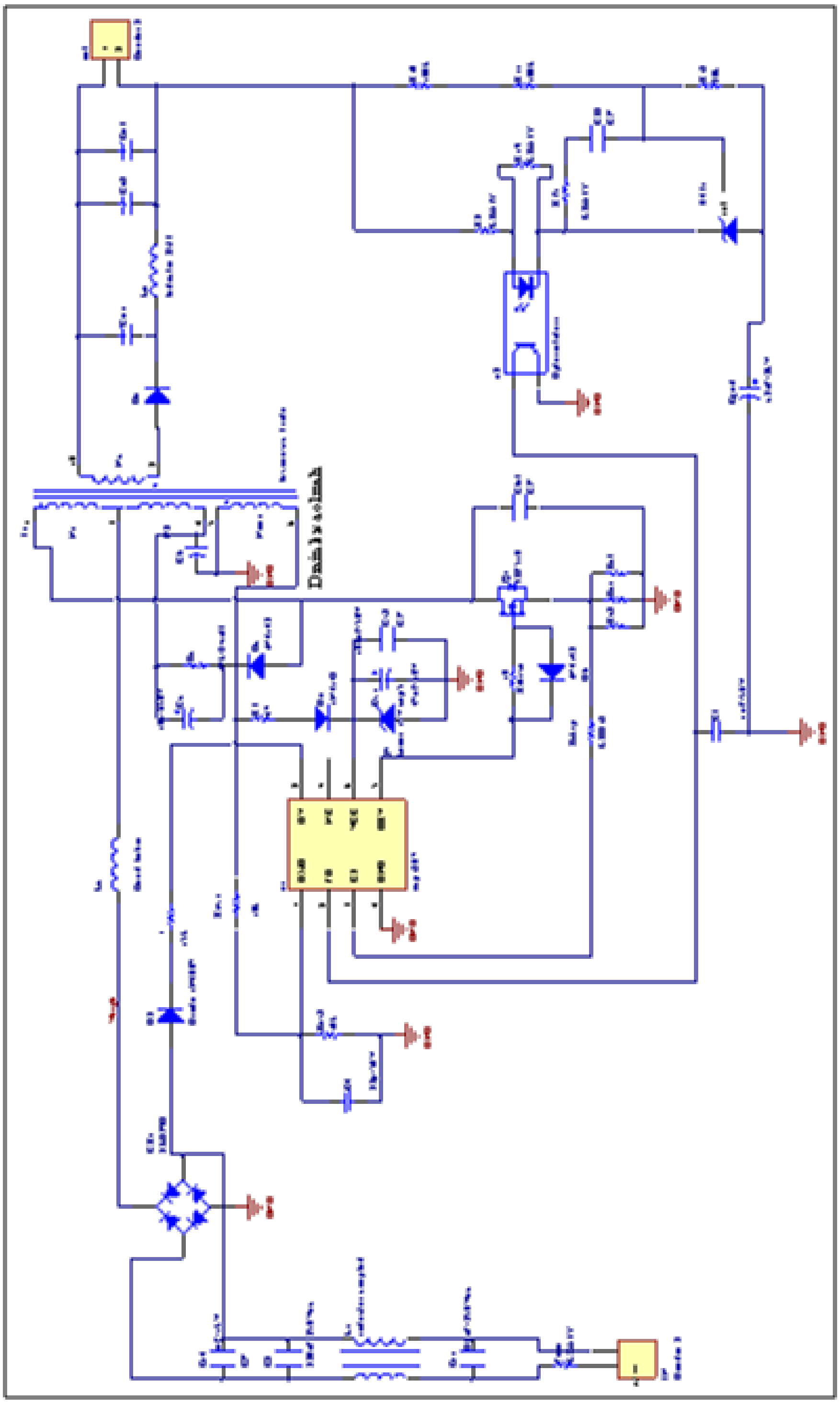


Figure 5.20 Flyback converter circuit layout

The manufacturing process continues with assembling the electronic components. This process involves several tests and implementation with several steps.

Flyback converter can be operated at both high and low line voltage. The only difference in two configurations is the change of boost inductor value. The experiments are performed for low line operation. Also the loading conditions are tested for different voltage levels. Researchers propose 0.90 power factor at full-load and performance values at different loading conditions. The experiments verify the performance values at low line voltage. However, experimental circuit performance at high voltage input has lower values than the proposed values of researchers. Next figure is the photograph of the flyback implementation circuit.

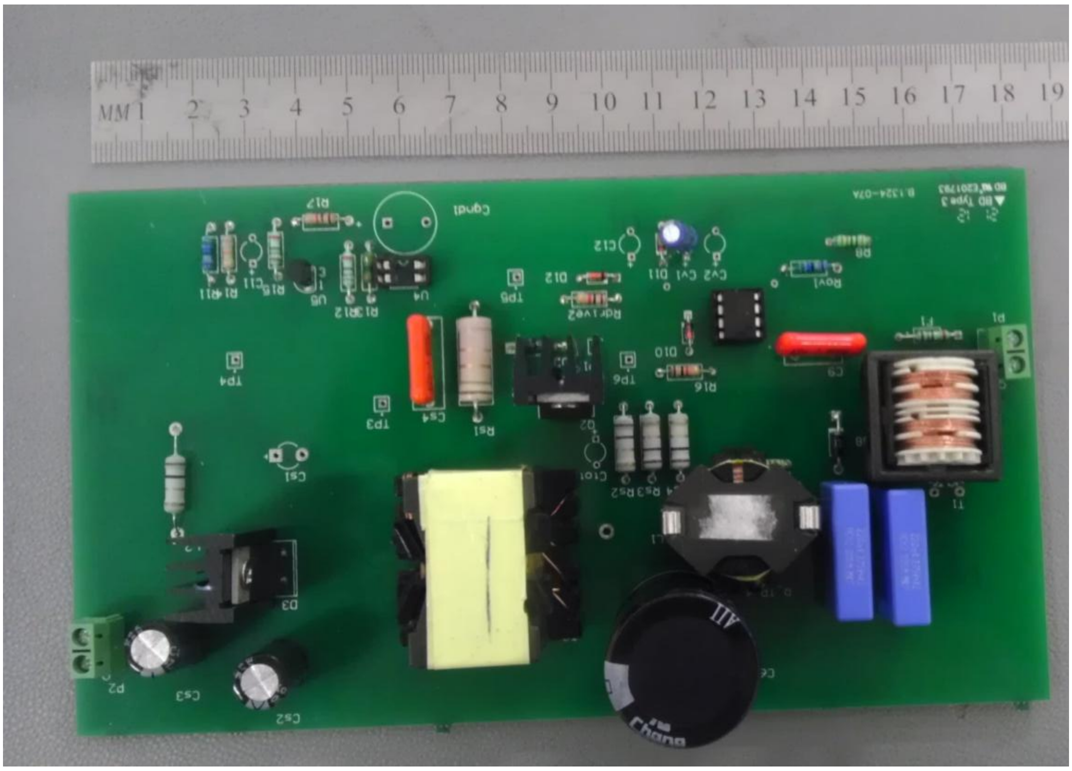


Figure 5.21 Flyback converter implementation circuit

5.5.2 Experimental Results of Flyback converter

This section introduces the experimental results of the manufactured converter. First point in the experiment is to operate the converter as a basic converter. After testing the converter's basic operation as converting AC line to a proper DC voltage level, over-heated points and the characteristic waveforms are detected. The characteristic waveforms show the parasitic of the converter, which affects the performance of the converter. Also the leakage currents heat the active components of the converter. One of the solutions is to use larger heat sinks for these devices and other solution is to decrease the parasitic by using passive elements and changing the layout of the converter. After these improvements the layout is renewed and the board is re-assembled. Second point is to test the converter for different values of components as it is tested in the research. This test shows the converter working condition change with respect to these components as the analytical calculations show and also the performance of the converter changes with respect to these components.

Here the experiments have to prove this converter improves the standard flyback converter in the manner of performance. This high performance device reaches high quality with low component and low cost. These experiments will deliver the optimum point for the converter operation for high quality and proper for the proposed operation of LEDs.

Another point is the feedback circuitry of the converter. There are various methods to control the flyback control. The experiments will also show the optimum method of flyback converter. Basically two methods are performed for feedback circuitry and both of them are successful for the correct operation of converter. First is the feedback from the secondary side with *opto-coupler* with basic op-amp comparator circuit. Second is the MOSFET voltage limit is defined by a signal taken from the rectified AC voltage. This signal ensures the MOSFET maximum current to follow a sinusoidal waveform. In future work, this signal can be modulated with respect to a value taken from the output voltage.

Figure 5.22 shows the current waveforms of critical components that show the mode of operation. Here it is shown that boost inductor operates in DCM mode of operation, and flyback transformer also operates in DCM mode of operation. Most of the time of operation transformer works in BCM mode. As it is mentioned in converter working principle part and design part sections; the operation modes are critical for the correct operation of the converter. During the experiments the effects of this restriction is tested, and result is the input line current is distorted if the boost inductor current moves to CCM mode of operation. The distortion occurs as a peak current at the highest level of the input voltage. This distort the power factor of the converter and reduce it down to 0.75.

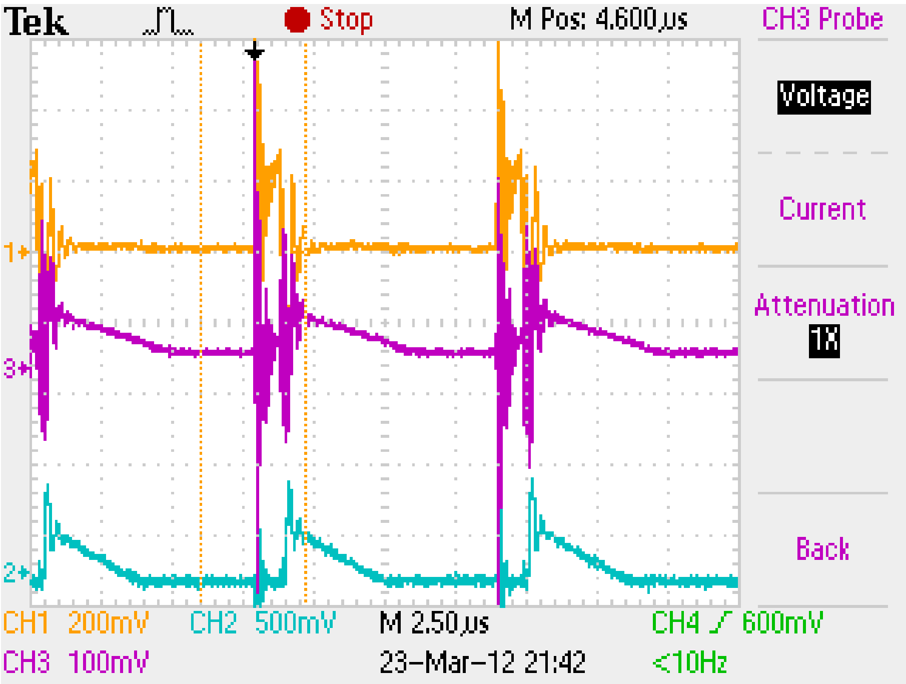


Figure 5.22 Flyback converter waveforms 110V, MOSFET current (yellow), boost inductor current (blue), secondary diode current (purple) (Scales: yellow 200 mV/div, purple 100 mV/div, blue 500 mV/div)

Here the values of these waveforms are critical to prove the analytical calculations and components values. MOSFET peak current is 1 A, peak boost inductor current is 1 A, and output diode peak current is 10 A. There are oscillations in the current waveforms, as a further work the layout of the converter and the components can be redesigned, in order to eliminate the parasitic of the converter.

Figure 5.23 shows the input line voltage and line current of the converter. In front of various waveforms and measurements of the converter, the fundamental performance result is line current and line voltage waveform of the converter. This test is performed at full load condition and the performance values are power factor as 0.9, THD_i 8.3% and output current is 3.25 as calculated. The input current value is distorted for most of the values; the optimum operation is at the boost inductance 150 uH and turn ratio 4/26.

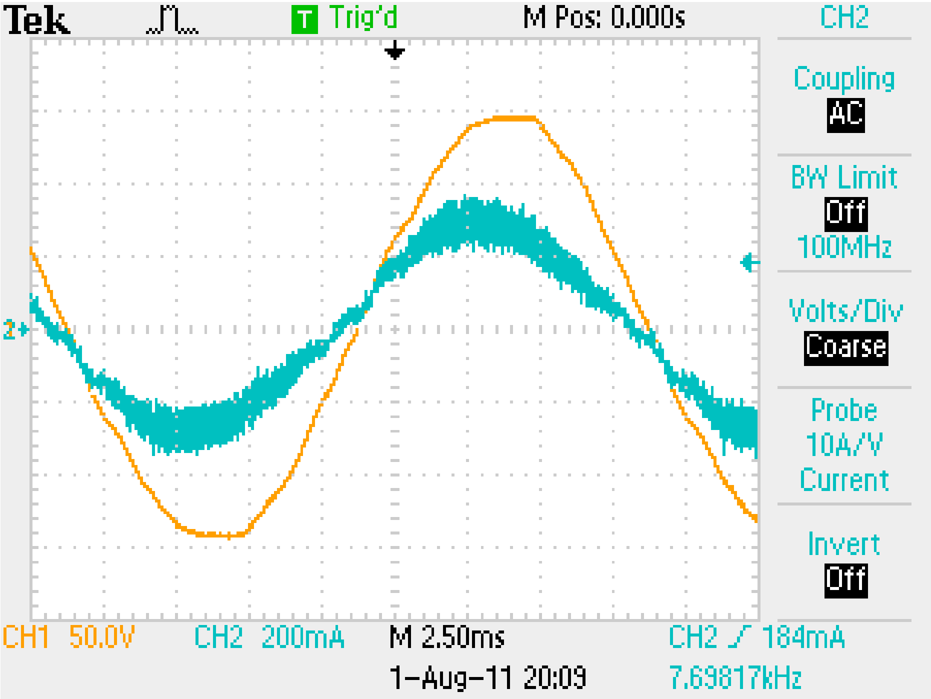


Figure 5.23 Flyback converter waveforms 110V input; input voltage (yellow), input current (blue) (Scales: yellow 50 V/div, blue 200 mA/div)

As it is observed from figure, input line current of the converter is nearly sinusoidal and follows the line voltage with a phase difference. Also there is a current ripple in the current waveform because of switching operation during power conversion.

The circuit performance is related to the working mode of the converter elements. The best results are obtained at the proposed mode of operation. These are the boost inductor works in DCM mode and the transformer operates in BCM mode. The following figures prove this operation mode. The waveforms are boost inductor, magnetizing inductor and output diode current. As it is opposed in converter operation, boost inductor releases its energy before the end of switching cycle.

Figure 5.24 illustrates the drain-to-source voltage waveform of the MOSFET. This waveform proves the quasi-resonance operation and the maximum value of the MOSFET. This waveform is significant for flyback converter, because MOSFET is one of the key elements of the converter and its operation is critical for efficiency and stability. As it is observed from figure, snubber circuit is successful for the component operation and switching action occurs at low voltage values.

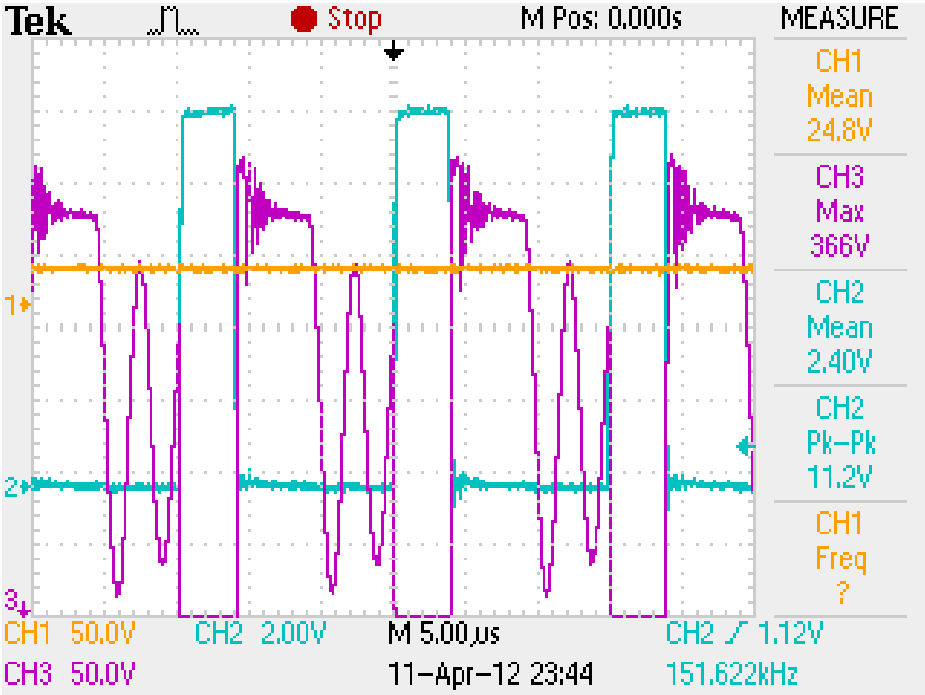


Figure 5.24 Flyback converter waveforms 220V, MOSFET voltage(purple), MOSFET gate voltage (blue) (Scales: Yellow 50 V/div, Purple 50 V/div, Blue 2 V/div)

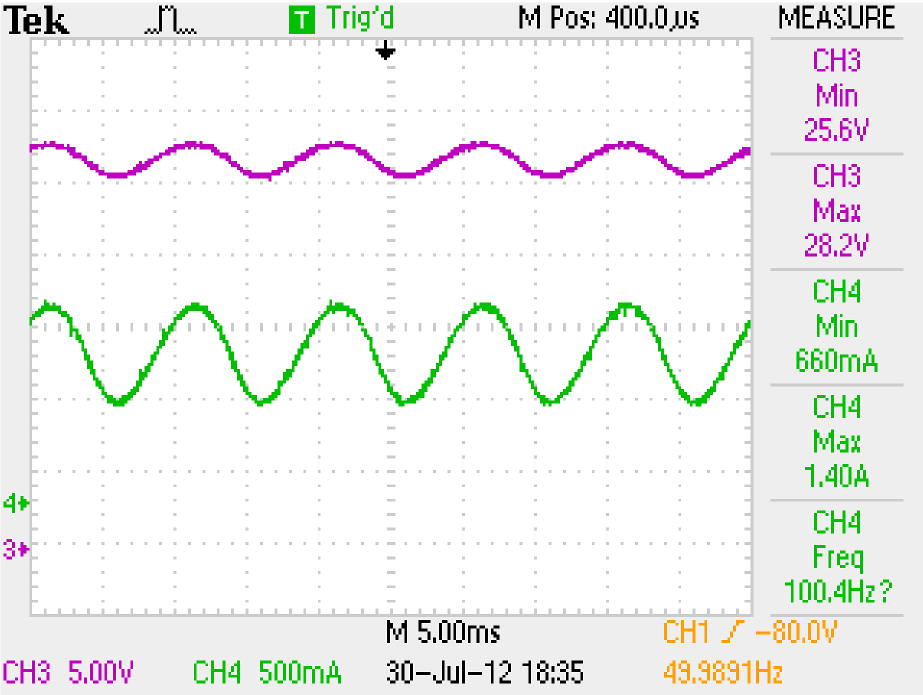


Figure 5.25 Flyback converter characteristic waveforms output voltage (purple), output current (green) (Scales: purple 5 V/div, green 500 mA/div)

Figure 5.25 shows the output voltage and output current waveforms of the converter. Output voltage has a ripple with double of the line frequency, as it is shown in analytical calculations and similarly to other single-stage converters. In the application there are multi branches as load. The output current waveform shows one of the branches as 850 mA constant current. Similarly to other converters, the output current has a large current ripple, which can be improved. However, this does not affect the application, since the current is constant during the operation.

After the working condition and the operation of the converter are approved, the performance of the converter is analyzed. This analyze covers the power factor and efficiency change with respect to loading. Converter has a high power factor value with 0.92 to 0.90 at full load condition. Converter is not designed for universal voltage range, so the tests are performed for different design values as mentioned in previous sections. Basically at high voltage levels, boost inductor value is 150 uH, and low line levels boost inductor value is 80 uH.

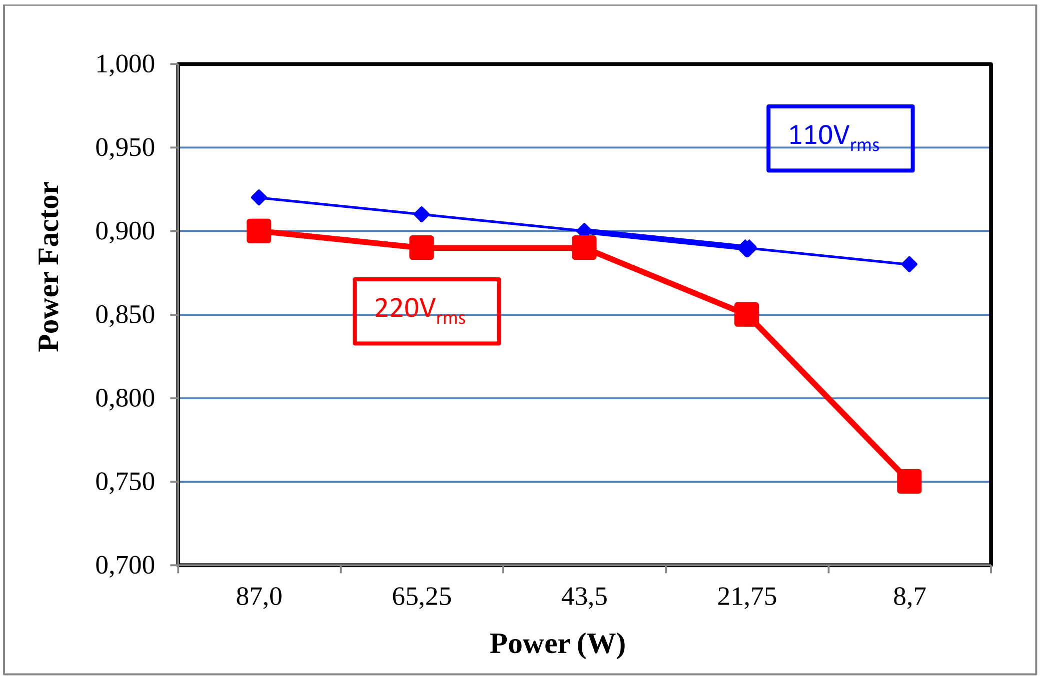


Figure 5.26 Flyback converter power factor change versus load

Next analysis is the efficiency change of the converter with respect to loading conditions of the converter. As it is opposed converter has higher efficiency value at low line input voltage and full load conditions.

Proposed converter improves power factor and efficiency value with respect to a same power traditional flyback converter without power factor correction stage. Also the converter improves efficiency with respect to a two-stage flyback power converter.

The converter power factor and efficiency decreases as the loading decrease. The load of the converter is HB LEDs. The loading is changed by decreasing the amount of the LEDs. The connected load is serial 6 LEDs and 90 parallel branches. Each branch has a linear drive circuitry in order to maintain the constant current operation. The branch number is decreased in order to obtain different loads. Efficiency value is 90 % at full load, however it decreases to 70% at light loads. This is one of the point that should be improved. Similarly the power factor value is high at full load, and decreased dramatically at light loads. This is another issue to be improved. The layout change will decrease the parasitic, and also the power loss.

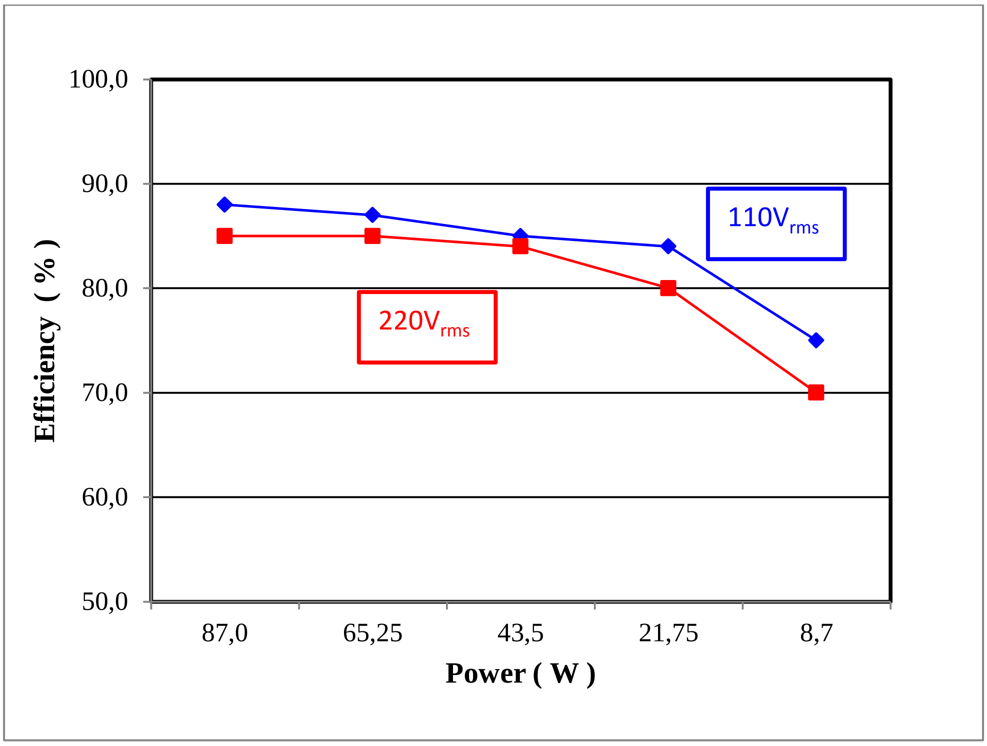


Figure 5.27 Flyback converter, efficiency change versus load

5.6 Chapter Conclusion

This section finalizes the implementation of proposed single-stage flyback converter. This chapter introduced; Flyback topology, analytical calculations, computer simulations and experimental verifications. Simulations and experiments verified that this arrangement, improves the performance of flyback converter with low cost. However, the experiment results were not perfect like the proposed converter. At low line input, the power factor is 0.92 and efficiency is 80%. At high line input, the power factor is 0.9 and efficiency is about 80%. The control system can be improved in order to improve the performance of the converter.

CHAPTER 6

REVIEW OF A HIGH POWER FACTOR FLYBACK BASED POWER SUPPLY, RECOM-30-700

6.1 Introduction

RECOM 30-700 power supply is a high performance LED driver developed for maximum 30 Watts of power. This power supply delivers constant current output and an output voltage range of 10 to 52 Volts. The power supply has topology of a flyback converter and the output stage has an extra constant current driver for LEDs.

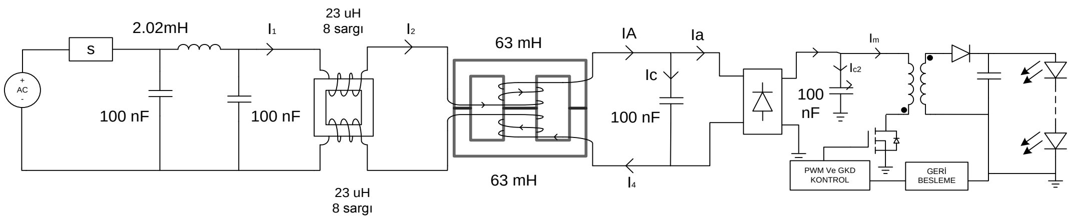


Figure 6.1 RECOM-30-700 basic layout

6.2 Flyback converter working principle

Flyback converter uses two integrated circuits but one switching component. The dc-dc stage interprets flyback converter and PFC application. After dc-dc stage another controller LM3404 is used to drive LEDs. Figure 6.2 and 6.3 introduce the schematic of the proposed converter.

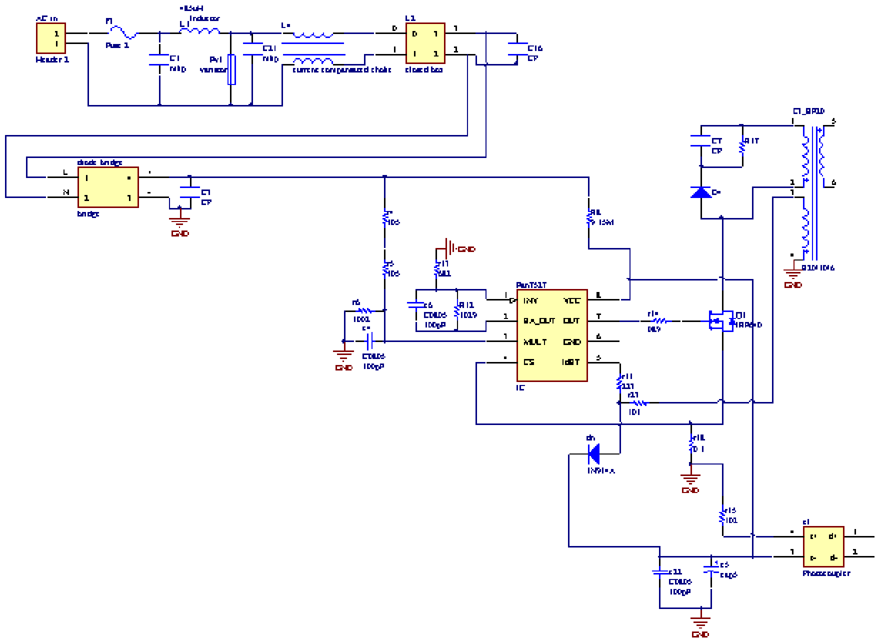


Figure 6.2 RECOM 30-700 converter schematic primary side

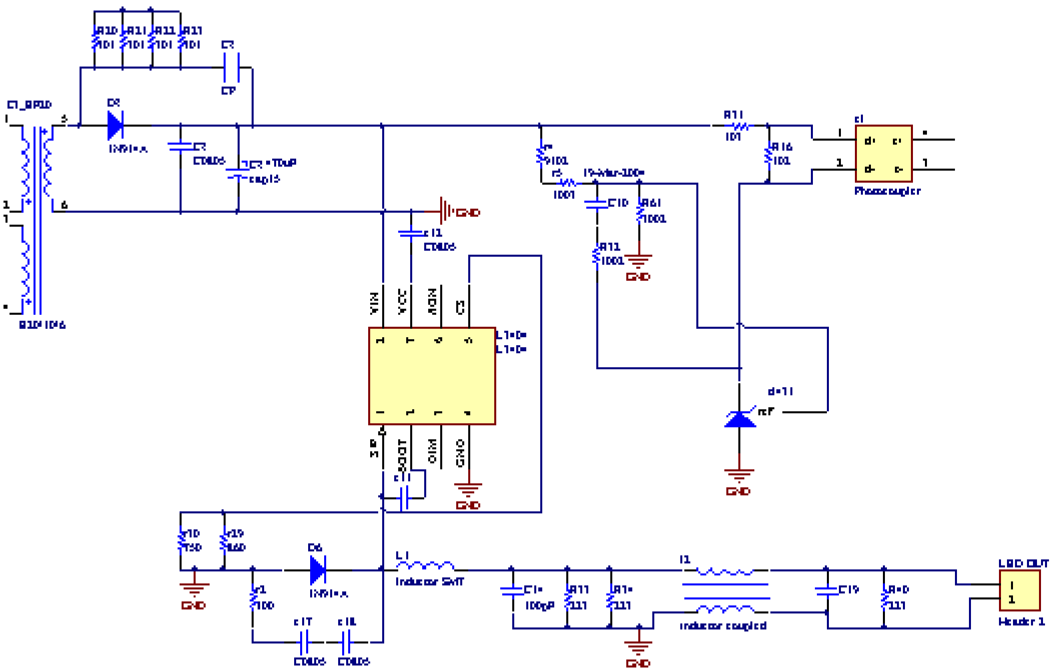


Figure 6.3 RECOM 30-700 converter schematic secondary side

6.3 Experimental Measurements of Flyback Converter

This section introduces the converter characteristic waveforms of the converter. First test is the input and output characteristic waveforms of the converter. Converter provides wide input voltage range operation and constant current in the output stage. Figure 6.4 introduces input voltage, input current, output voltage and output current waveforms of the converter. As it is observed from the figure, input current has a sinusoidal waveform and follows the input voltage waveform. This shows that the power quality of the converter is good, which will be detailed in following section. Output voltage and output current waveforms have an oscillation at double of the line frequency, which is a common property of single-stage converters. Output power of the converter is 29 W and output current is 700 mA with peak to peak ripple of 430 mA. This margin is proper for LED load, since the maximum current value is in the margin of maximum of LED current.

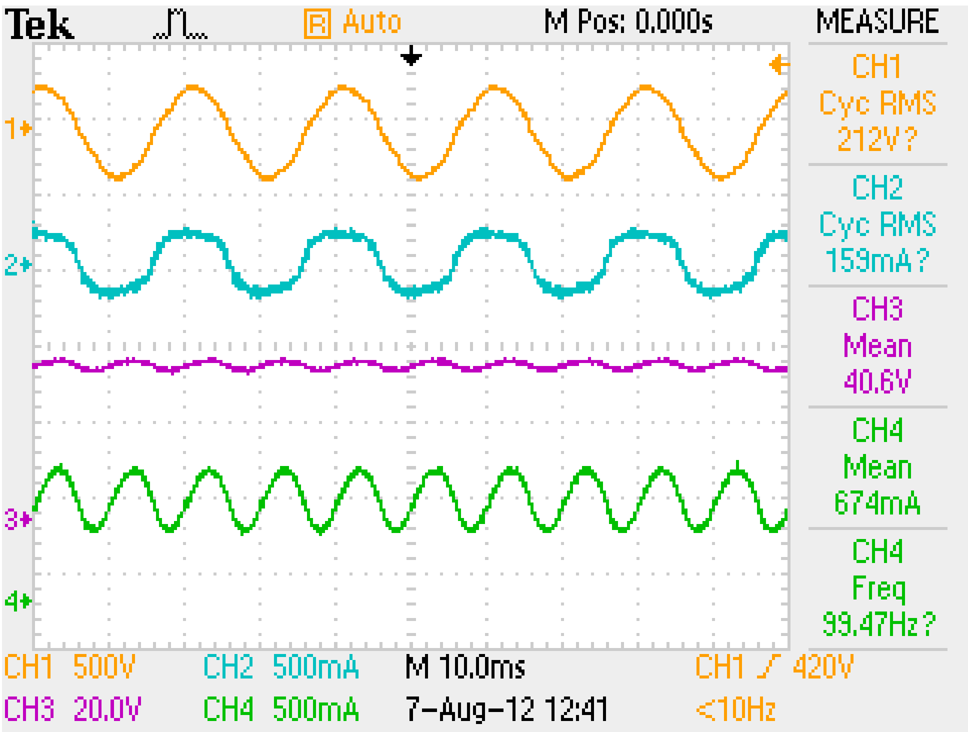


Figure 6.4 Converter waveforms: Input voltage (yellow), input current (blue), output voltage (purple), output LED current (green) (Scales: yellow 500 V/div, purple 20 V/div, green 500 mA/div, blue 500 mA/div)

Figure 6.5 introduces input voltage and current waveforms with input power measurements. This measurement shows us input power is 31.8 W and power factor value is 0.947 as it is intended in the properties of the converter.

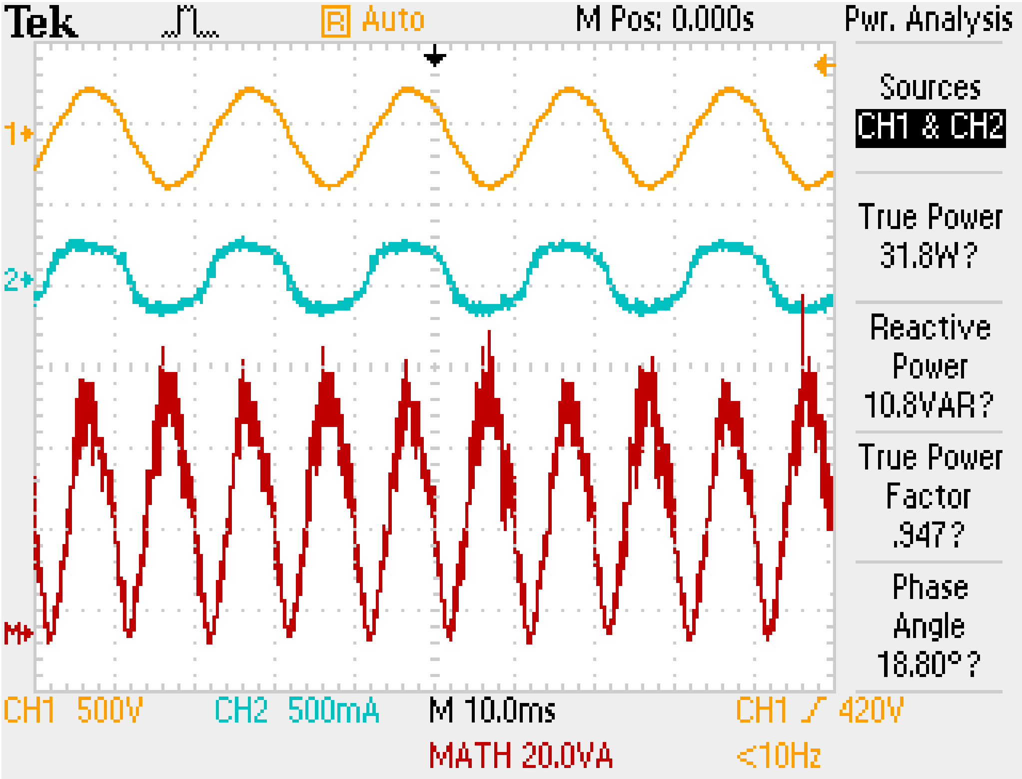


Figure 6.5 Converter waveforms, input voltage (yellow), input current (blue), input instantaneous power (red) (Scales: yellow 500 V/div, blue 500 mA/div)

Figure 6.6 shows output voltage and output current characteristic waveforms. Also, minimum and maximum values are detailed in the figure. The voltage and the current values are in the range of operation of LED load. LED drive current value changes from 470 mA to 900 mA, which means peak to peak ripple of 430 mA. However, important value is the average of this current waveform, because LED is a DC power source and DC current value is the average value of this waveform. Measured value for average current is 700 mA as it is intended in the converter properties. Converter provides this value in all of the input voltage range of operation. In addition this current change does not effects the application, because

LED light output is relevant to average current, and it is also constant for different input voltages.

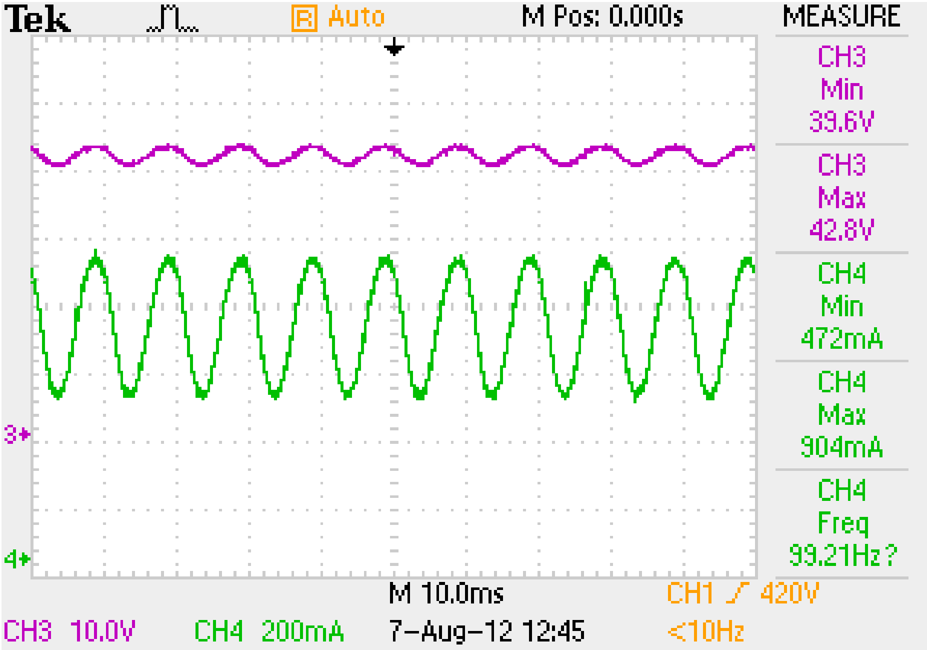


Figure 6.6 Converter waveforms, output voltage (purple), output current (green)
(Scales: Purple 10 V/div, Green 200 mA/div)

Table 6.1 details the converter characteristic functions and output values for full load conditions at high line input.

Table 6.1 Converter characteristic properties

Parameter	**Value**	**Unit**
True Power	31.8	W
Reactive Power	10.8	VAR
Power Factor	0.947	Non-unit
Efficiency	85%	Non-unit
Output Current Mean value	674	mA
Output Current Minimum Value	472	mA
Output Current Maximum Value	904	mA
Output Current Peak to Peak Value	432	mA
Output Voltage Mean Value	40.6	V
Output Voltage Minimum Value	39.6	V
Output Voltage Maximum Value	42.8	V
Output Voltage Peak to Peak Value	3.2	V

6.4 Performance Results of Flyback Converter

This section involves the performance results for the proposed power supply. Power quality measurements and operation measurements are performed for different voltage levels and different loading levels. First measurement is the power factor change with respect to different load levels as shown in figure 6.7.

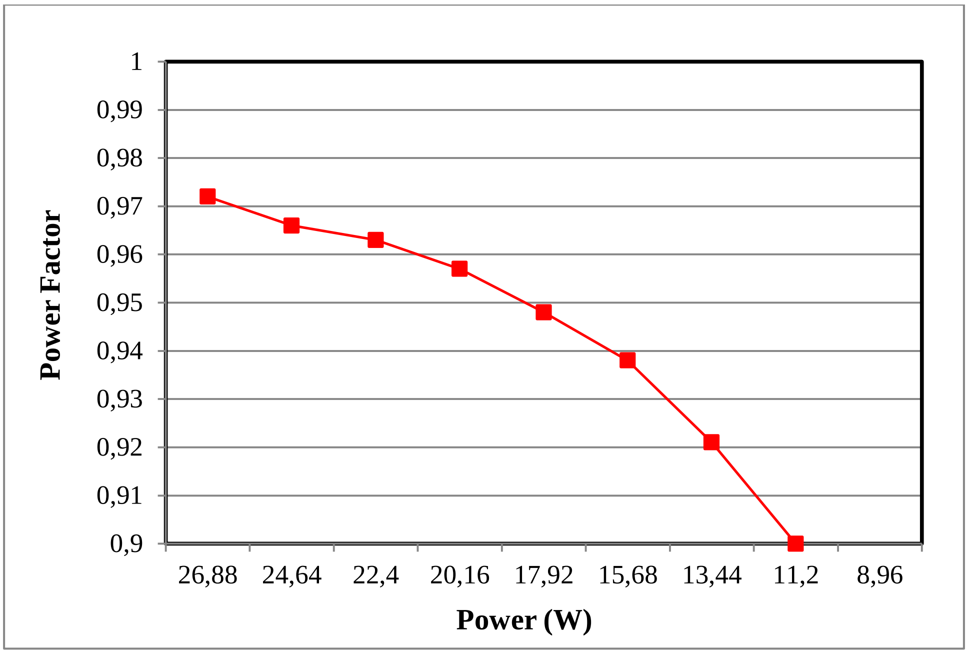


Figure 6.7 Converter performance analysis, power factor value at different loads

Intended power factor value of the converter in its specifications is 0.95. As it is observed from the figure, power factor value changes from 0.97 to 0.9 with respect to loading conditions. Similarly to other converters best value occurs at full loading conditions, because of the design of the converter. This phenomenon is similar for efficiency value of the converter as shown in figure 6.8. Efficiency of the converter is 95% at full load conditions and it declines to 85% for low loading conditions. Converter efficiency is very high with respect to other converters in market and in researches.

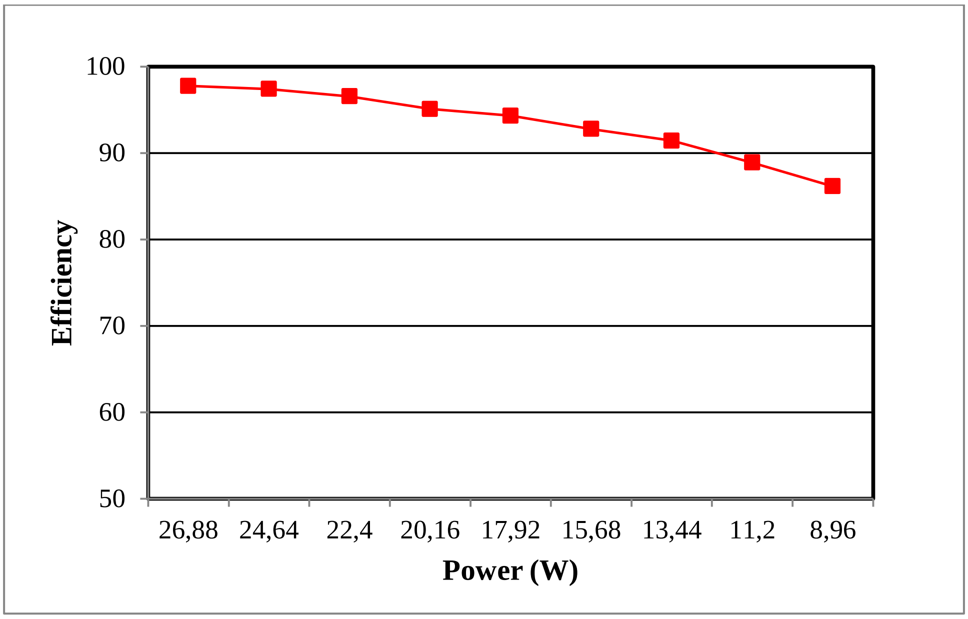


Figure 6.8 Converter performance analysis, efficiency value at different loads

6.5 Chapter Conclusion

Investigated power supply, RACD-30-700 from RECOM, is a high quality and high performance LED driver proper for applications about 30 W. Converter is designed to provide constant output current with a value of 700 mA. In addition, converter can be used from 10% load to 100% loading condition. This property is important because luminaries manufacturers prefer to use single power converter for different LED applications. This converter will be reviewed with respect to the researched and manufactured converters in our research. This product is manufactured with respect to several products and it is a commercial product in the market.

CHAPTER 7

CONCLUSION

20TH century was the time for societies to adaptation to new energy, electrical power. Lighting is one piece of this cake with a twenty percentage of the electrical power consumption. In this century, lighting systems became widespread which went to any place where people live. 21TH century is the time for understanding how world suffers from the growing consumptions of societies and consuming the sources of world carelessly.

One of the precautions for decreasing the energy consumption is energy saving. The energy savings on lighting intends to reduce energy consumption with new technologies of light sources and manufacturing efficient power electronic devices for light equipment. The new technology, light-emitting-diodes, led the line of energy savings as a new light source. In addition, this new light source needs special type of power converters in order to operate in correct conditions. Therefore, LEDs have to be used with proper and efficient power converter devices.

Developed power converters for AC to DC conversion are switch-mode power supplies. These converters developed with power factor correction stages, with high power quality and performance features. These converters adapted to LED loads according to several standards. Since 1990s a new technology in this area, is researched and developed which is single-stage power supplies. SSPS are high performance devices like two-stage power supplies; however they have low cost with respect to these power supplies. In this thesis the two encouraging technology LEDs and SSPS are tried to be combined, in order to obtain a systematic solution for energy saving and cost problems.

The first chapter introduced the light sources with developments from the beginning of 20^{th} century. Afterwards, the new power electronic devices introduced as point of this research. The second chapter introduced the new light source, LEDs, with historical developments, technological basis and the manufactured products. Also, the light definitions introduced to provide knowledge about the applications of LEDs. This chapter provided the electrical and thermal characteristics of LEDs. Final part presented the appropriate electrical power for LEDs and standards for LED power supplies.

The third chapter introduced various power electronic devices for LEDs. This chapter introduced power electronic devices according to developments from the preliminary devices to high efficiency devices. Also, some examples are introduced for different LED applications. Next, high performance devices presented as power supplies with elevated performance. After the establishment of these power supplies, the point of the research single-stage power supplies introduced.

The following three chapters were researched power supplies for LEDs. These devices are compromised solutions between different types of converters; single-stage SEPIC converter, single-stage flyback converter with unique configuration and high performance power supply from market. Therefore, these converters analyzed thoroughly; by analytical solutions, MATLAB calculations of waveforms, computer simulations and experimental verifications.

SEPIC converter experiments were perfectly successful and consistent to proposed performance features, with analytical calculations and experimental verification. SEPIC converter is designed for LED applications for maximum 30 Watts and works with universal input voltage range. SEPIC converter has the property of converting the energy in one stage, and with few control signals, input line current can match the input line voltage. Experimental results obtained at V_{in} =110 V_{ac} , output 21 LEDs and I_{LED} = 0.35 A converter achieved high power factor as 0.995, efficiency around 80% and total harmonic distortion (THD) of 4.5% for the line current with harmonic contents meet IEC 61000-3-2 Class C standard. Experimental results obtained at V_{in} = 220 V_{ac} , output 21 LEDs and I_{LED} = 0.35 A converter achieved high power factor as 0.99, efficiency around %80 and total harmonic distortion (THD) of 5.5% for the line current with harmonic contents meet IEC 61000-3-2 Class C standard. Converter proposes dimmable LED current opportunity which is a need for lighting applications. In addition line current harmonics are reduced. SEPIC converter efficiency is about 80%; most of the power loss occurs at the power supply circuit of integrated circuits and active elements. This issue was indicated and the solutions are leaved as further work. SEPIC converter is a high performance design and the application range makes this converter feasible in various applications.

Flyback converter with unique configuration aimed to increase the efficiency and performance of standard flyback converters. The proposed configuration integrates DC-DC stage and PFC stage of a flyback converter and provides power conversion in one stage. The proposed converter designed for 90 Watts. This power levels need more attention in design and similar commercial products in this power level is high cost devices. The proposed converter reduces the component count, the size and cost of the converter. In this thesis, analytical solutions approved the operation system of the converter, however the simulations and experimental verifications showed that performance could not give proposed performance values of the research. The research suggests several different values for passive elements and finally some limits are defined for these parameters. Experiments are performed for different parameters of transformer and boost inductor and best results are listed in the research. Similarly the experiments followed in the same way, testing different value for boost inductors and changing the turn ratio values of transformer. Experimental results obtained at V_{in} =110 V_{ac}, output 216 HB-LEDs, output voltage V_o = 24 V and each LED current is I_{LED} = 50 mA. Here the LEDs have series transistor to limit the current through it because the proposed converter delivers constant voltage. Converter achieved power factor of 0.90, efficiency of 90% and total harmonic distortion (THD) of 14% for the line current with harmonic contents meet IEC 61000-3-2 Class C standard. The proposed converter is a cost-efficient solution, but the performance can be improved as a further work. The control system of the converter can be redesigned in order to operate converter in better conditions. In addition this proposed solution can be applied to various power levels, because most of the power supplies are designed as a flyback converter for LED applications.

Final converter is a flyback converter from the market and commercially available. This converter is a high performance device but high cost solution. This converter is detailed with performance tests in order to compare to the SEPIC and special flyback converter. Table 7.1 compares the three converters.

Table 7.1 Comparison table of selected single-stage power supplies

Feature	Flyback Converter	SEPIC converter	RECOM 30-700
Power Factor	0.90-0.92 for low line	0.99-0.95	0.95-0.90
Power Quality	Good	Best	Very Good
Operating Voltage	Design Changes	Universal	Universal
Output Voltage	24 V (adjustable)	12- 100V	12-56 V
Output Current	3.25 A	0-0.350 mA	0.700 mA
LED Connection	Low String	Higher String	Medium
Efficiency	85%	80%	90%
Cost / Watt	Best	Good	Bad
Standards	Most (Future Work)	Most	All
Application	Limited	Best	Limited

Three power supplies are designed with different output voltage and output current levels but all of them are used for LED applications. As it is listed in the table, three converters are feasible solutions for different features. From the point of power factor best solution is the SEPIC converter. The flyback converter, RACD-30-700 has the highest efficiency with respect to others. Special flyback converter is the best cost effective solution; even the special flyback converter is designed for higher power level than the others. Here the comparison is performed in the manner of cost per watt performance of the devices.

Another parameter is the application of the converters. LEDs have various types of applications, but in most of them LEDs are tried to use in high amounts in a product. For example a wall-washer product that lights the facade of buildings, has minimum 48 LEDs. The perfect operation of LEDs is connecting them serially, which brings the need of high voltage. Therefore, SEPIC converter is feasible for most of LED application. Even this property is related to output power and output current value of the converters, there is few products in the market for LEDs proposing high voltage in the range of 30 Watts.

As it is mentioned, standards for LED lighting and LED power supplies are proposed in these years. It is seemed that LED will be the major lighting element in next 10 years, this prediction brings that, the standards have to be carefully defined with causing the products to be high quality.

There are various parameters when designing a product; unfortunately it is not limited with technical parameters. Designer has to be careful about its cost, its application and its performance. As a result of this thesis, single-stage power supplies are low-cost and high performance devices for a limited range of power. Another material, LEDs are low power, efficient lighting products and developing each day. The developments occur with respect to applications. And it is feasible when its cost became comparable with the other lighting elements. Here the two technology; LEDs and single-stage power supplies perfectly match. As a summary three converters are feasible solutions, with respect to the application. These power converters and further converters have to be analyzed and designed to be used in LED applications, in order to manufacture more efficient and low cost devices. In this manner, LED will be applied in most of the places with low cost and energy consumption of lighting equipments will decrease.

REFERENCES

[1] Rondeau, L. (2011) *The Effects of Efficient Lighting in the USA.* Energy Economics and Policy-ETH Zurich

[2] Illumintaıng Engineering Soceity of North America. (2005, August 12). Nomeclature and Definition for Illuminating Engineering. *ANSI/IESNA RP-16-05* Newyork

[3] Lenk, R., & Lenk, C. (2011). *Practical Lighting Design with LEDS.* NJ: IEEE Press

[4] E. Fred Schubert, “Light-Emitting Diodes” *Cambridge University Press,* 2003

[5] Zukauskas, A., Shur, M. S., & Caska, R. (2002). *INTRODUCTION TO SOLID-STATE LIGHTING.* New York: John Wiley & Sons, Inc

[6] Cree Inc., *Optimizing PCB Thermal Performance For Cree XLamp LEDs,* 2010

[7] Osram, “Lighting Plus Lead Free Product”, LE CW S2LN datasheet, Dec. 2010

[8] Institute of Electrical and Electronics Engineer, “The LED’s Dark Secret” Available: http://www.spectrum.ieee.org/semiconductors/optoelectronics/the-leds-dark-secret [Accessed: August 2012]

[9] Wikipedia.,Available:*en.wikipedia.org*.http://en.wikipedia.org/wiki/Luminous_efficacycite_note-ideal-white-7

[10] Eric E.Richman “Requirments for Lighting Levels” Pacific Northwest National Laboratory

[11] Cree Inc., “Cree XLamp XP-E High-Efficiency White LEDs” XP-E HEW datasheet, 2010

[12] Winder, S. (2008). *Power Supplies for LED Driving.* Burlington: Elseiver.

[13] DC or AC supplied electronic control gear for LED modules-Performance requirements, British Standard 62384:2006

[14] Electromagnetic Compatibility (EMC), Part 3-2: Limits – Limits for harmonic current emissions (equipment input current ≤ 16 A per phase), International Standard IEC, 61000-3-2, 2001.

[15] R. H. Muhammad, “Power Electronics: Circuits, Devices and Applications”, *Prentice Hall*,1993.

[16] L. L. Fang, Y. Hong, “Power Electronics: Advanced Conversion Technologies”, *CRC Press,* 2010

[17] Texas Instruments, “LM3404/04hv, 1.0A Constant Current Buck Regulator for Driving High Power LEDs” LM3404 datasheet, 2010

[18] Texas Instruments, “LM3421, LM3423 N-Channel Controllers for Constant Current LED Drivers”, LM3421 datasheet, 2010

[19] Fairchild Semiconductor, “AN-9736, Design Guideline of AC-DC Converter Using FL6961&FL6300A for 70W LED Lighting” AN-9736 application note, 2011.

[20] I. Takahashi and R. Y. Igarashi, “A switching power supply of 99% power factor by the dither rectifier,” in Proc. IEEE-INTELEC’91 Annu. Meeting, 1991, pp. 714–719.

[21] R. Redl, L. Balogh, and N. O. Sokal, “A new family of single stage isolated power factor correctors with fast regulations of the output voltage,” in Proc. IEEE-PESC’94 Annu. Meeting, 1994, pp. 1137–1144.

[22] C. Qiao, K.M. Smedley, “A topology survey of single-stage power factor corrector with a boost type input-current-shaper” in Proc. IEEE Appl. Power Electron. Conf. (APEC), Feb. 2000, pp.460-467.

[23] L. Huber, J. Zhang, M. M. Jovanovic, and F. C. Lee, “Generalized topologies of single-stage input-current-shaping circuits,” IEEE Trans. Power Electron., vol. 16, pp. 508–513, July 2001.

[24] M.T. Madigan, R.W. Erickson, E.H. Ismail, “Integrated high-quality rectifier-regulators”, IEEE Transactions on Industrial Electronics, Vol. 46, No. 4, August 1999.

[25] Q. Zhao, F.C. Lee, F. Tsai, “Voltage and current stress reduction in single-stage power factor correction ac/dc converters with bulk capacitor voltage feedback” IEEE Transactions on Power Electronics, Vol. 17, No. 4, July 2002.

[26] Y. Hu, L. Huber, M.M. Jovanovic, “Single-stage flyback power-factor-correction front-end for HB LED application” Proc. of IAS 2009, Oct. 2009

[27] L. Huber and M.M. Jovanovic, “AC/DC flyback converter”, U. S. Patent No.6950319, Sept. 2005

[28] Y. Hu, L. Huber, M. M. Jovanovic, “Universal-input single-stage PFC flyback with variable boost inductance for High-brightness Led applications”,

[29] Z. Ye, F. Greenfeld, Z. Liang, “Design considerations of a high power factor SEPIC converter for high brightness white Led lighting applications” IEEE Power Electronics Specialists Conference, 2008

[30] V. Vorperian, “Simplified analysis of PWM converters using model of PWM switch Part 2: discontinuous conduction mode” IEEE Transaction on Aerospace and Electronic Systems, Vol. 26, pg.497-505, 1990.

[31] R. Ray, “Analyzing the SEPIC converter” Power System Design Europe, 2006

[32] D. S. Simonetti, J. Sebastian, J. Uceda, “The discontinuous conduction mode Sepic and Cuk power factor pre-regulators: analysis and design” IEEE Transactions on Industrial Electronics, Vol. 44, No. 5, 1997.

[33] J. Sebastian, J. A. Cobos, J. M. Lopera, J. Uceda, “ The determination of boundaries between continuous and discontinuous conduction modes in PWM dc-to-dc converters usd as power factor pre-regulators” IEEE Transactions on Power Electronics, Vol. 10, No. 5, 1995.

[34] Intersil, “ISL6745EVAL2Z offline high brightness white LED driver with high power factor for universal input” ISL6745EVAL2Z application note, 2009

[35] Intersil, “ISL6745 Bridge controller with precision dead time control” ISL6745 datasheet, 2005

[36] On Semiconductor “NCP1207A, NCP1207B, PWM current-mode controller for free-running quasi-resonant operation” NCP1207A datasheet, 2009.

APPENDIX A.1

COLOR RENDERING INDEX

This table introduces the comparison of the color rendering index values of different light sources.

Table A.1 Light sources comparison with respect to color rendering index

Light source	CCT (K)	CRI
Low-pressure Sodium (LPS/SOX)	1800	~5
Clear Mercury-vapor	6410	17
High-pressure Sodium (HPS/SON)	2100	24
Coated Mercury-vapor	3600	49
Halophosphate Warm-white Fluorescent	2940	51
Halophosphate Cool-white Fluorescent	4230	64
Tri-phosphor Warm-white Fluorescent	2940	73
Halophosphate Cool-daylight Fluorescent	6430	76
White LED	2700	82
Quartz Metal Halide	4200	85
Tri-phosphor Cool-white Fluorescent	4080	89
Ceramic Metal Halide	5400	96
Incandescent/halogen Bulb	3200	100

APPENDIX A.2

PHOTOMETRIC UNITS

Light is defined with photometric units in order to compare the light sources. These are introduced in the following table.

Table A.2 Photometric quantities, symbols and definitions

Quantity	Symbol	SI unit	Symbol	Notes
Luminous energy	Q_v	lumen second	lm·s	Units are sometimes called *talbots*
Luminous flux	Φ_v	lumen (cd·sr)	lm	Also called *luminous power*
Luminous intensity	I_v	candela (= lm/sr)	cd	SI base unit, luminous flux per unit solid angle
Luminance	L_v	candela per square metre	cd/m^2	Units are also called *nits*
Illuminance	E_v	lux (= lm/m^2)	lx	Used for light incident on a surface
Luminous emittance	M_v	lux (= lm/m^2)	Lx	Used for light emitted from a surface
Luminous exposure	H_v	lux second	lx·s	
Luminous energy density	ω_v	lumen second per metre^3	lm·s·m^{-3}	
Luminous efficacy	η	lumen per watt	lm/W	Ratio of luminous flux to radiant flux
Luminous efficiency	V	Non-unit		Also called *luminous coefficient*

APPENDIX B.1

CIRCUIT LAYOUT OF SINGLE STAGE SEPIC CONVERTER

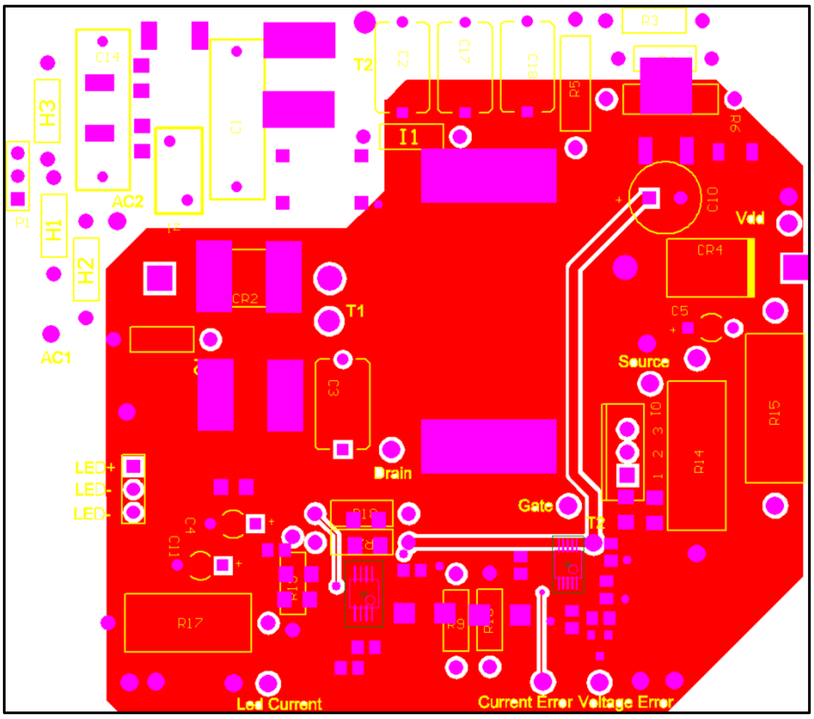


Figure B.1 SEPIC converter board top side circuit layout

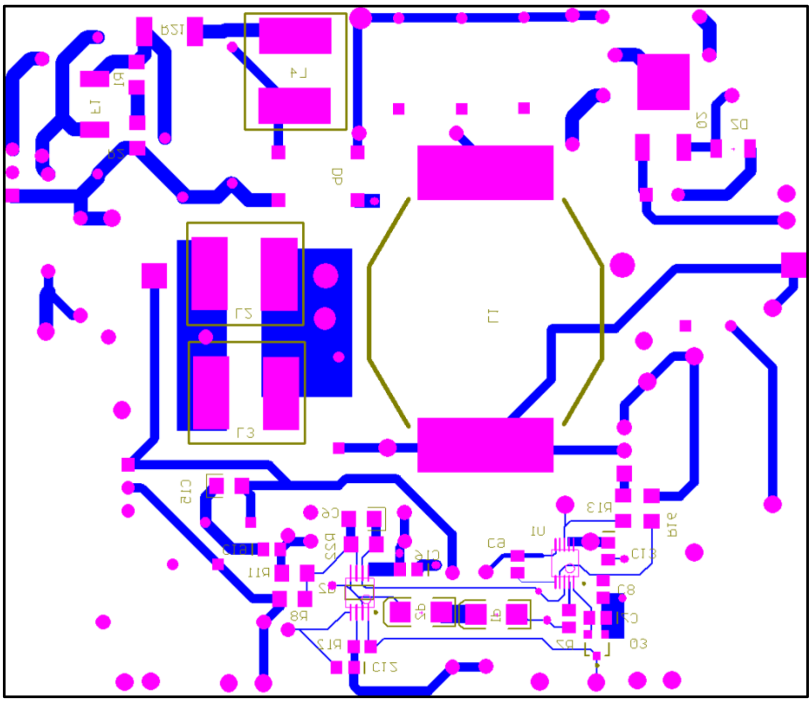


Figure B.2 SEPIC converter board bottom side circuit layout

APPENDIX B.2

CIRCUIT LAYOUT OF SINGLE FLYBACK CONVERTER

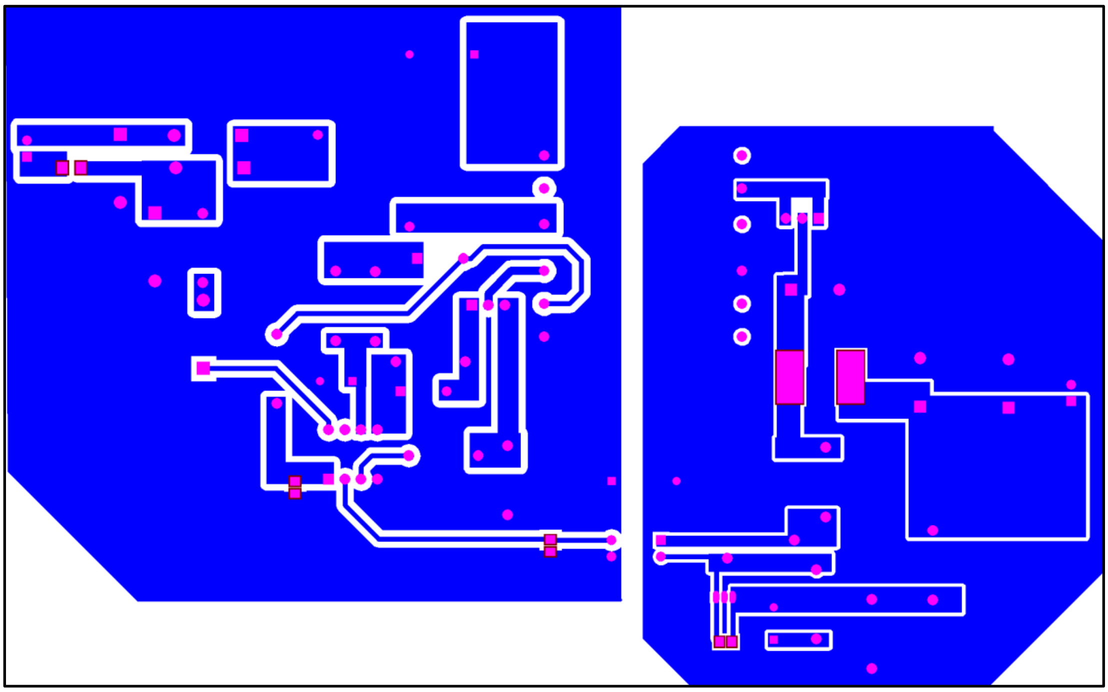


Figure B.3 Flyback converter board bottom side circuit layout

APPENDIX C.1

MATLAB CODE FOR SEPIC CONVERTER CHARACTERISTIC FUNCTIONS

```
%*******************************************************************
% BY: Hasan YILMAZ
% Date: 30/06/2012
%*******************************************************************
% Matlab code defines the characteristic functions of SEPIC
converter
% Line waveform and one switching cycle are divided to 100 pieces;
half line period has
% 10001 parts. Each part the parameters are recalculated.
Calculations are performed with
% respect to the equations developed in chapter 4.


% Parameters of the converter

Vo    = 73;                   % output voltage
Io    = 0.4;                  % output current
Vl    = 370;                  % peak input voltage
wl    = 2*pi*50;              % line frequency
fs    = 150000;               % switching freuqency
Ts    = 1/fs;                 % switching period
Teta  = [0:pi/100:2*pi];
v1    = Vl*sin(teta(2:100)); % line voltage
M     = Vo/Vl;                  % Sepic transfer constant
Ka_c  = 0.5/((M+1)^2)      % K constant for DCM operation
Rip   = 0.35;                     % Current ripple constant
Ka    = 0.3;                       % K-factor
d     = (sqrt(2))*M*(sqrt(Ka));    % duty cycle limit
Ton   = d*Ts;                     % switching on time
Idr   = 1;                     % Mosfet drive current
Q     = 2*Idr*Ts               % Mosfet drive charge


%% Converter Voltage and Current functions

Vmax = Vl+Vo;                                 % Maximum MOSFET voltage
Imax = Vl*((1/L1)+(1/L2))*Ton;                % Peak Line current
Iav  = Imax*Ton/(2*Ts);                       % Average MOSFET current
Ip   = Ts.*v1.*((1/L1)+(1/L2)).*(Vo./(Vo+v1)); %Peak MOSFET current
Iq   = v1.*((1/L1)+(1/L2)).*(teta(2:100))/(2*pi*fsw);%Peak diode
current
```

```
duty  = Vo./(Vo+v1);                          % Converter duty cycle
I1    = Vl*(d^2)*Ts/(2*Leq);      % Primary current
I1_rip   = Rip*I1;               % Primary current ripple
idiode_p = Vl*d*Ts/Leq;       % SEPIC secondary diode current;


%% Converter Passive Elements

L1    = Vl*d*Ts/I1_rip            % Primary inductance
L2    = (L1*Leq)/(L1-Leq)         % Secondary inductance
fr    = 16740;                    % Resonance frequency
c1    = 1/(((2*pi*fr)^2)*(L1+L2))% SEPIC capacitor
L     = (1/L1)+(1/L2);              % Equivalent inductance
C1_s  = 4*(Krpi^2)*Ts*d*Vo*Io/(Krpv*(Vl^2)*L2) % Input capacitance
Co_s  = (Vl*I1)/(2*Vrpp*Vo*wl) % Output capacitance


% MATLAB waveform generator
% This part generates the current waveforms with calculated
variables

iq    = zeros(101,101);
id    = zeros(101,101);
%iq_tam=zeros(1,10201);
for i=1:1:101
    for j=1:1:101
        if(j<100*D(i))
            iq(i,j)=vsin(i)*L*(Ts*j/100);
            id(i,j)=0;
        else
            iq(i,j)=0;
            if ((vsin(i)*D(i)*Ts)-(Vo*(Ts*j/100)))>0
                id(i,j) = L*((vsin(i)*D(i)*Ts)-(Vo*(Ts*j/100)));
            else
                id(i,j) = 0;
            end

        end

    end
end
iq_tam=zeros(1,10201);
id_tam=zeros(1,10201);
for i=1:1:101
    for j=1:1:101
        iq_tam(1,((i-1)*101)+j)=iq(i,j);
        id_tam(1,((i-1)*101)+j)=id(i,j);
    end
end

iq_rms=sqrt(mean(iq_tam.^2))
id_rms=sqrt(mean(id_tam.^2))
```

APPENDIX C.2

MATLAB CODE FOR CHARACTERISTIC FUNCTIONS OF FLYBACK CONVERTER

```
%*******************************************************************
% BY: Hasan YILMAZ
% Date: 30/06/2012
%*******************************************************************
%Matlab code defines the characteristic functions of Flyback
%converter
%Line waveform and one switching cycle are divided to 100 pieces;
%half line period has 10001 parts. Each part the parameters are
%recalculated. Calculations are performed with
%respect to the equations developed in chapter 5.



%% Converter input and output characteristics

Teta  = (0:pi/100:2*pi);            % Mains line period
Vrms  = 110;                        % Line voltage RMS value
vin   = sqrt(2)*Vrms*sin(teta);     % Line voltage
fline = 50;                         % Line frequency
Tline = 1/fline;                    % Line period
Vo    = 24;                         % Output voltage
Io    = 3.25;                       % Output current
Eout  = Vo*Io*Tline/2;              % Converter energy

%% Converter parameters
%% Transformer parameters

N1    = 4;        % Primary winding, first turn
N2    = 26;       % Primary winding, second turn
Np    = N1+N2;    % Primary winding
Ns    = 5;        % Secondary winding
N     = Np/Ns;    % Primary/secondary turn ratio
n1    = N1/Np;

%% %% Passive Elements and Capacitor Voltage

Lb    = 120e-6;         % Boost inductance
Lm    = 650e-6;         % Magnetizing inductance
Vb    = 175;            % Bulk capacitor voltage
Vn1   = n1*Vb;          % Primary winding voltage

%% Duty cycle calculation
```

```
D2     = zeros(1,101);          % Second duty cycle time
D1     = n*Vo/(Vb+(n*Vo));      % Primary duty cycle time
for i=1:1:101
    if(vin(i)>Vn1)
    D2(i)= (vin(i)-Vn1)*D1/(Vb+((N2/Ns)*Vo)-vin(i));
    else
    D2(i)= 0;
    end
end

%% Frequeny calculation

a    = (n^2)*Vo/Lm;
for i=1:1:101
    d (i)   = (((1-D1)^2)-(D2(i)^2));
    b (i)   = (N2/Ns)*(vin(i)-(n1*Vb))*D1/Lb;
    Tjs(i)  = 2*Io./((((a*D2(i))+b(i))*D2(i))+(a*d(i)));
    fjs(i)  = 1/Tjs(i);
end


%% Converter current functions

ilb_p = zeros(1,101);       % boost inductor current peak value
ilb   = zeros(101);           % boost inductor current
ic_p  = zeros(1,101);        % bulk capacitor current peak value
ic    = zeros(101);          % bulk capacitor current
imos  = zeros(1,10201);      % total of ic and ib
iin   = zeros(1,101);
iin_wide =zeros(101);

is1=zeros(101);
is1_p=zeros(101);
is2=zeros(101);
is2_p=zeros(101);
is=zeros(101);

io=zeros(1,101);

io_wide=zeros(101);
for i=1:1:101
    for j=1:1:101
        if(vin(i)>Vn1)
            if (j<100*D1)
                ilb(i,j)  = (vin(i)-Vn1)*D1*Tjs(i)*j/(100*Lb);
                ilb_p(i)  = ilb(i,j);
                ic_p(i)   = ilb_p(i)*(D2(i))/D1;
                is1_p(i)           =            (n*(1-n1)*ilb(i,j))+
(((n^2)*Vo/Lm)*(D2(i))*Tjs(i));
                is2_p(i)  = ((n^2)*Vo/Lm)*(1-D1-(D2(i)))*Tjs(i);
                ic(i,j)   = -ic_p(i)*j/(D1*100);
                a(j)=1;
            elseif (j>100*D1 && j<100*(D1+D2(i)));
```

```
                    ilb(i,j)=ilb_p(i)-((ilb_p(i))*(j-
(100*D1))/(100*(D2(i))));
                    is1(i,j)=is2_p(i)+is1_p(i)-((is1_p(i))*(j-
(100*D1))/(100*(D2(i))));
                    a(j)=3;
            else
            ilb(i,j)=0;
            is1(i,j)=0;
            is2(i,j)=is2_p(i)-((is2_p(i))*(j-
(100*(D2(i)+D1)))/(100*(1-(D1+D2(i)))));
            a(j)=5;
            end
        else
            ilb(i,j)=0;
            is1(i,j)=0;
            is2(i,j)=0;
            ic(i,j) =0;
        end
    end
    io(i)=(is1_p(i)*(D2(i))/2)+(is2_p(i)*((D2(i)+(1-D1)))/2);
    iin(i)=ilb_p(i)*(D1+(D2(i)))/2;
end
is=is1+is2;
ilb_tam=zeros(1,10201);
is_tam=zeros(1,10201);
ic_tam=zeros(1,10201);
iin_tam=zeros(1,10201);
io_tam=zeros(1,10201);
for k=1:1:101
    iin_wide(k,:)=iin(k);
    io_wide(k,:)=io(k);
end
for i=1:1:101
    for j=1:1:101
        ilb_tam(1,((i-1)*101)+j)=ilb(i,j);
        is_tam(1,((i-1)*101)+j)=is2(i,j);
        iin_tam(1,((i-1)*101)+j)=iin_wide(i,j);
        io_tam(1,((i-1)*101)+j)=io_wide(i,j);
        ic_tam(1,((i-1)*101)+j)=ic(i,j);
    end

end

imos    =(n1*ilb_tam)-ic_tam;
imos_rms=sqrt(mean(imos.^2));
imos_a  =(sum(imos))/10201;
is_rms  =sqrt(mean(is_tam.^2));
iin_rms =sqrt(mean(iin_tam.^2));
io_rms  =sqrt(mean(io_tam.^2));
ilb_rms=sqrt(mean(ilb_tam.^2));
```