A NEW LED DRIVER DESIGN WITH CRM FLYBACK TOPOLOGY AND HIGH POWER FACTOR AND LOW TOTAL HARMONIC DISTORTION

A Thesis

by

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Submitted to the

Graduate School of Sciences and Engineering
In Partial Fulfillment of the Requirements for
the Degree of

Master of Science

in the
Department of Electrical and Electronics Engineering

Özyeğin University
January 2018

A NEW LED DRIVER DESIGN WITH CRM FLYBACK TOPOLOGY AND HIGH POWER FACTOR AND LOW TOTAL HARMONIC DISTORTION

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To my family and memory of my grandmother…

ABSTRACT

In many of today's solid-state lighting (SSL) applications, Critical Conduction Mode (CRM) Flyback PFC converter is a popular solution due to its limited component count and simple structure with respect to other switched mode power supply (SMPS) topologies. As described in international standards documents (IEC/EN 61000-3-2), LED drivers are required to demonstrate a power factor results greater than 0,9 and lower total harmonic distortion (THD) for power levels above 25W. Due to nonsinusoidal input current waveform of the traditional constant-on time control method, achieving improved PF and THD is quite difficult. In this thesis after introduction to LED lighting and switch mode power supplies, a new control method is introduced in an effort to improve power factor and total harmonic distortion of Voltage Mode CRM Flyback PFC Converter. The work proposes injection of a compensating $\sin(wt)$ signal component in the feedback path utilizing an additional primary transformer winding to linearize the current from the source. The detailed theoretical analysis is presented along with measurement results of a 30W prototype.

ÖZETÇE

Günümüzdeki aydınlatma uygulamalarının birçoğunda kritik iletim modlu flyback güç faktörü düzeltici konvertörü, sınırlı malzeme sayısı ve diğer anahtarlama modlu güç kaynakları topolojilerine göre basit yapısı nedeniyle popüler bir çözümdür. Uluslararası standart belgelerinde (IEC / EN 61000-3-2) açıklandığı gibi, LED sürücüleri, 25 W üzerindeki güç seviyeleri için 0,9'dan büyük güç faktörü ve düşük toplam harmonik bozulma sonuçlarını göstermek zorundadır. Geleneksel sabit-zamanlı kontrol yönteminin sinüzoidal olmayan giriş akım dalga biçimi nedeniyle, geliştirilmiş güç faktörü ve toplam harmonik bozulma elde etmek oldukça zordur. Bu tezde, LED aydınlatma ve anahtarlama modlu güç kaynaklarına giriş yapıldıktan sonra Gerilim Modlu kritik iletim modlu flyback güç faktörü düzeltici konvertörün güç faktörü ve toplam harmonik bozulmasını iyileştirmek için yeni bir kontrol yöntemi önerildi. Bu tez, kaynağın akımını doğrusallaştırmak için ek bir birincil transformatör sargısı kullanan, geri besleme yolunda telafi eden bir $\sin(wt)$ sinyal bileşeninin enjeksiyonunu önermektedir. Ayrıntılı teorik analiz, 30W'lık bir sistem prototipinin ölçüm sonuçlarıyla birlikte sunulmaktadır.

ACKNOWLEDGMENTS

I am deeply grateful to my advisor Asst. Prof. Ahmet TEKİN because of his support and guidance. He gave insightful comments and suggestions to me.

I would also like to thank my colleagues Cengiz Tarhan and Tayfun Küççük and Vestel Electronics R&D power lab team for their help and support.

Most importantly, special thanks to my loving and supportive wife Pınar Kavcı and my wonderful child Enes Kavcı for their patience. Their support is invaluable. Without their understanding and support, this thesis would not have been possible.

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CHAPTER I

INTRODUCTION

1.1 Introduction to LED Lighting

In recent years, light emitting diode (LED) based lighting systems have proliferated rapidly, due to various opportunities involved such as longer life time, lower power dissipation, lower maintenance cost, environment friendly operation and inherently controllable. LED Lightings are used in a wide range of home and industrial products [1][2][3][4][5][6][7][8].

A light emitting diode (LED) is a diode which converts electricity into light with respect to the current flows through its semiconductor structure. The diode is formed by equivalent combination of p-type and n-type semiconductor. Anode is the area where the p-type semiconductor is located and cathode is the area where the n-type semiconductor is located. When the LEDs are polarized in the direction of conduction, free electrons enter the anode through the p-n junction. Some of them merge with the holes in them. The energy that is dissipated by this union is the form of light energy. The value of the current flowing through the p-n junction depends on the number of electrons and holes. All diodes release photons, but not all diodes emit light just light emitting diodes. The material in an LED is selected so that the wavelength of the released photons falls within the visible portion of the light spectrum. Different colors are obtained by changing the materials used in LED production because of different materials produce photons at different wavelengths. (GaAs, GaP, GaAsP) The structure of LED is showed in Figure 1.1 [2][8][9].

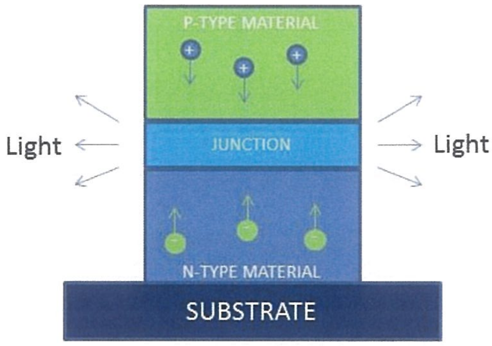


Figure 1.1: The structure of LED

There are two basic types of LEDs. These are illuminator type LEDs and indicator type LEDs. Indicator type LEDs are inexpensive and generally low power LEDs. Illuminator type LEDs are more durable than indicator type LEDs and can be used for high power devices. The anatomy of the illuminator type LED is showed with Figure 1.2 [1][2].

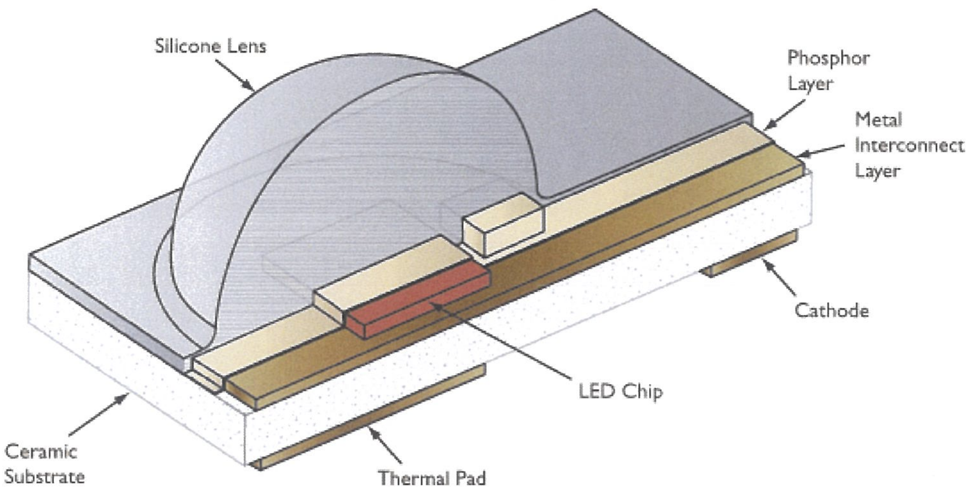


Figure 1.2: The anatomy of LED [2].

Nick Holonyak Jr. is the inventor of the first visible-spectrum LED in 1962. Then the LED technology has constantly improved and costs have dropped significantly. And due to its advantages, LEDs became a good solution for lighting. Global sales of LED replacement bulbs increased by 22 percent and the cost of a 60 watt equivalent LED bulb cheapened by nearly 40 percent between 2011 and 2012. By 2030, LEDs are estimated to account for 75 percent of all lighting sales [10]. With the costs of energy and new requirements for high efficiency lighting, LED market is expanding rapidly. Solid-state lighting (SSL) is the market name of this technology [3][5][11][12][13].

1.2 Power Supplies

Every electronic devices which do not work with battery, requires a converter that converting AC voltage to some DC voltage. In simple terms DC Power supplies are devices converting AC input signal to DC output signal for energy required at electronic devices [1][5]. There are two main types of DC power supplies.

- Linear Power Supplies
- Switched Mode Power Supplies

Linear power supplies and switched mode power supplies utilize various techniques to regulate output from unregulated input.

Linear power supplies can only step down an input voltage to a lower output voltage by a switching component with its linear operating mode. Because of this operation mode, dissipated power is high. Due to the fact that dissipated power causes temperature, the cost of the heatsink increases. For these reasons, linear power supplies are not economical and efficient solution for step down applications. But linear power supplies are simple and cheap because of requiring few components. And they don't have high frequency switching noise [4][9][14].

Switched mode power supplies are more efficient than linear power supplies. The switching component creates an AC voltage from the input DC voltage. This voltage is be stepped down or stepped up with transformer and filtered back to DC at its output. However, the design of switched mode power supplies are more complex and the output voltage contains switching noise [4][9][14][15].

Consequently, both are used according to usage requirements for many applications.

Table 1.1: COMPARISON OF SMPS AND LINEAR POWER SUPPLIES

	SMPS	**LINEAR POWER SUPPLIES**
Circuit Design	Complex	Simple
Part Count	High	Medium
Efficiency	70-95%	40-60%
EMI	High	Low
Size	Small	Large
Power	High	Low
Weight	Light	Heavier
Power Factor	0.5 - 0.95	0.6 - 0.7
Isolation	Yes	Yes

1.3 SMPS Topologies for LED Lighting

LED driver is defined as *"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"* by Illuminating Engineering Society of North America [16]. Every day technology is evolving rapidly and products are being smaller and lighter. For this reason, drivers of products must be smaller and lighter. In order to reduce size and improve the efficiency, switching mode power supplies are popular choice [3][17]. Switching mode power supplies regulates output voltage with high frequency switching technique and complex structure. As you can see from Table 1.1, switching power supplies are smaller and more efficient than linear power supplies [8]. The block diagram of Switched mode power supplies are shown in Figure 1.3.

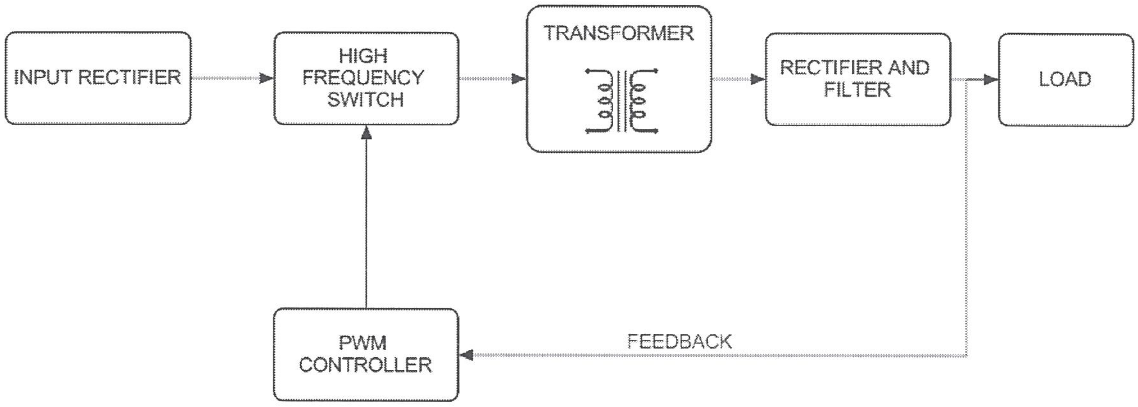


Figure 1.3: The block diagram of SMPS

There are two basic types of PWM modulated switched mode power supplies, the forward mode and the boost mode. The step down converter is a basic forward mode controller, which is shown in the Figure 1.4. With L-C filter on the output a DC output voltage is creating [14].

$$V_{out} \approx V_{in} \, . \, Duty \tag{1.1}$$

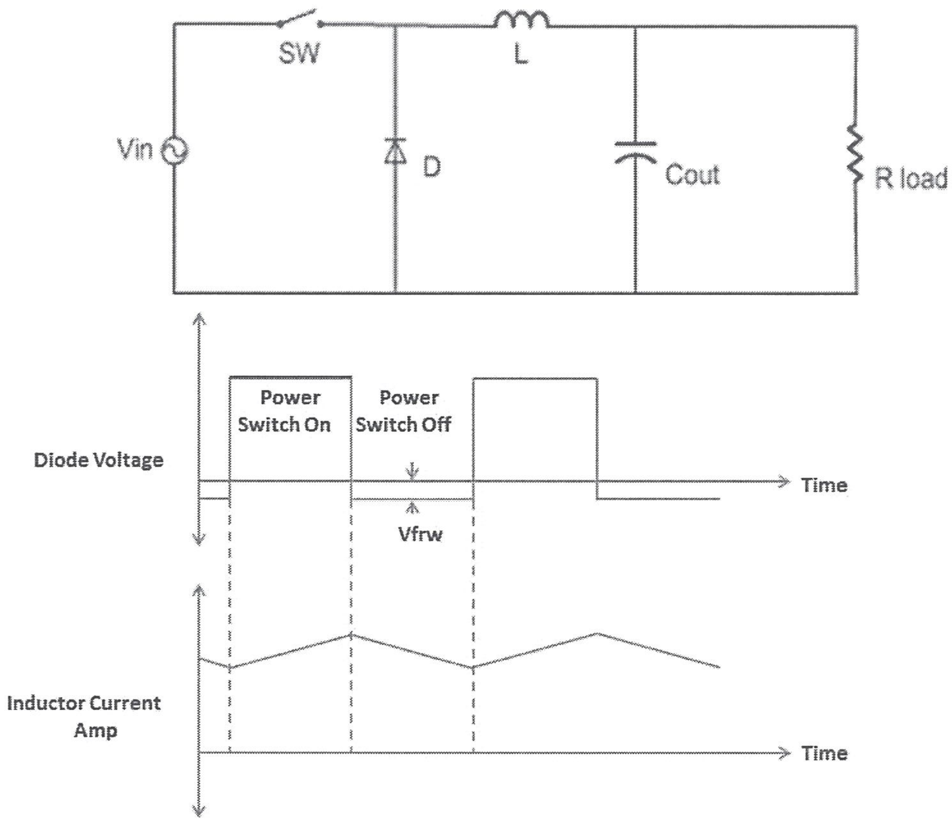


Figure 1.4: A basic Buck converter and its waveforms

The basic Boost mode converter works with a different configuration of same components, which is shown in Figure 1.5.

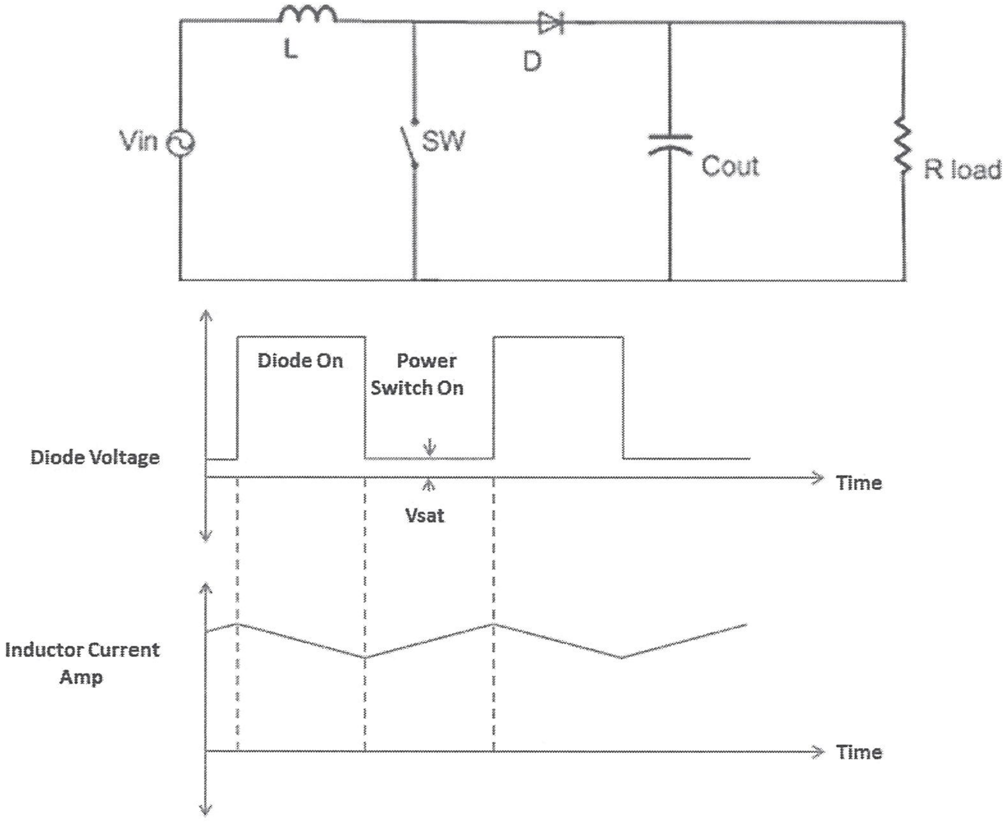


Figure 1.5: A basic Boost converter and its waveforms

Topology is the arrangement of the rectification, switching and energy storage components that involved in the switching mode power supplies. Although there is a lot of topology option, there is no single topology that is good for all SMPS applications. The correct topology should be selected according to some features such as output power level, cost, dimensions, current ripple, total efficiency, EMI, isolation. The most used topologies are given below [5][14][18][19]. Due to the fact that all the topologies are not the main theme of this study, it will stay with this explanation and focus will be on Flyback.

- Non-Isolated Converters
    - ➢ Buck (Step Up) Converter

- Boost (Step Down) Converter
- Buck-Boost (Inverting) Converter
- SEPIC Converter

- Isolated Converters
  - Flyback Converter (Hard Switching)
  - Forward Converter (Hard Switching)
  - Two Switch Forward Converter (Hard Switching)
  - Push-Pull Converter (Hard Switching)
  - Half Bridge Converter (Hard Switching)
  - Full Bridge Converter (Hard Switching)
  - Quasi Resonant Flyback (Soft Switching)
  - Half Bridge Resonant (Soft Switching)
  - Full bridge Resonant (Soft Switching)
  - Active Clamp Forward

The flyback converter is derived from Buck-Boost converter. It is used for power levels below 150W generally [14]. The basic circuit diagram of the flyback converter is showed in the Figure 1.6. In a flyback converter Q_1 switch is connected serially to transformer primary side. The transformer is used to store the energy during the on time of the switching component. The relation between input and output voltages of flyback converter are shown in equation (1.2) where N_s is the secondary winding turns, N_p is the primary winding turns and D is the duty of the system [19].

$$\frac{V_{out}}{V_{in}} = \frac{N_s}{N_p} \cdot \frac{D}{1-D} \tag{1.2}$$

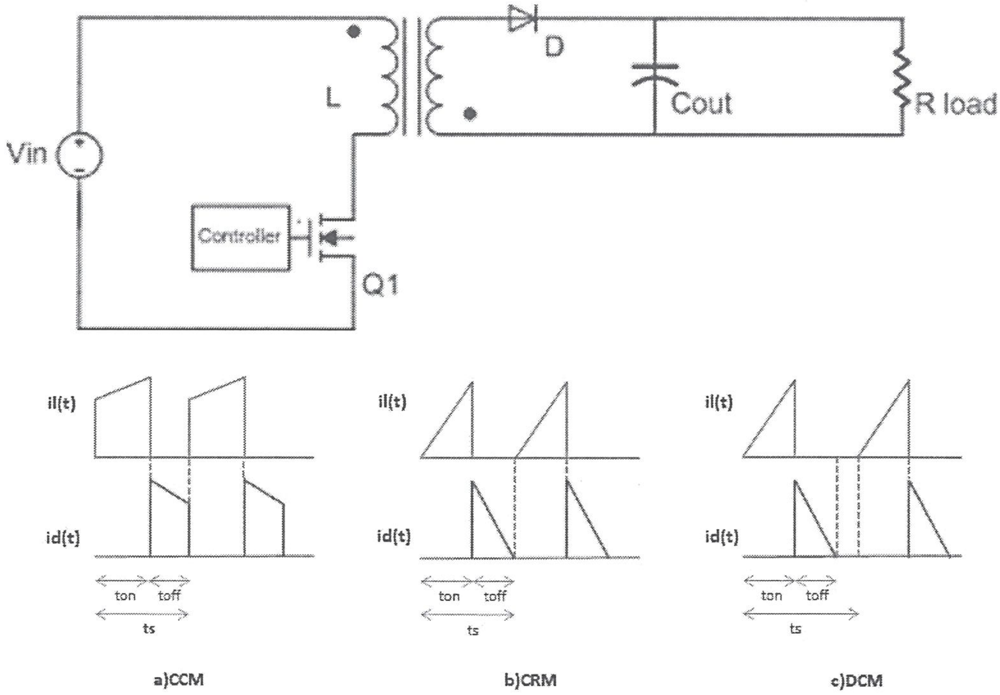


Figure 1.6: A basic Flyback converter and its waveforms

In order to obtain good performance with LEDs, power supply and driving technique is too crucial [20]. For solid-state lighting applications, high power factor single stage flyback converter is a popular choice due to reduced overall system, component count and significantly simpler implementation with respect to other switch mode power supply topologies [5][7][8][21].

1.4 Scope of Thesis

The main scope of the thesis is the research of the critical conduction mode flyback PFC converter for solid-state lighting applications and improving total harmonic distortion and power factor of CRM flyback PFC converter. This study includes theoretical analysis and experimental results of proposed control strategy.

Chapter 1 is the introduction to the LEDs and switch mode power supplies. First part is the introduction to LEDs and solid-state lighting applications. Next part is explanation of power supplies. Then switched mode power supplies and topologies for LED lighting are explained.

Chapter 2 involves the theoretical analysis of Flyback PFC converters. Firstly conduction modes described. Then critical conduction mode and constant on time control method for flyback converters are described. Finally proposed control scheme is described.

Next chapter, low THD and high PF CRM Flyback PFC circuit is designed and analyzed. In order to optimize THD and PF, an improved control strategy is proposed. Moreover the experimental results of a sample prototype are presented at 30W power levels to confirm the theoretical expectations.

The main focus of this thesis is analyzing CRM Flyback PFC converter for solid-state lighting and improving the PF and THD of the converter.

CHAPTER II

THEORY

The power factor can be defined as the ratio of the real power and the apparent power simply. The difference between real power and apparent power is reactive power. Because of reactive power, the heat of the power cords or transmission lines and the source will be higher. And it causes need more current to achieve the desired output power. Overall with the higher input current, energy loss of the converter will be increased. And the cost of compensating electrical equipment will be higher [8][14][22][23].

$$Power\ Factor = \frac{P(Real\ Power)}{S(Apparent\ Power)} \tag{2.1}$$

If the load is pure resistor, the power factor of the system is 1. If the load is linear load which consist inductors, resistors and capacitors, the voltage and the current will be a sine wave with same phase. And the relation between P and S will be like equation (2.2). In there cos θ is named as displacement power factor (DPF) [23].

$$|P| = |S| \cos\theta \tag{2.2}$$

If the load is non-linear, the input current waveform may distort and apparent power includes all harmonics. It is named as distortion power factor. So, the total power factor of the non-linear system is the displacement power factor multiplied by the distortion power factor. And it is showed with equation (2.4) where, θ is the phase angle between current and voltage, $I_{1,rms}$ is the fundamental component of the current and I_{rms} is the total current [22].

Current total harmonic distortion (THD) is the distortion of the input current due to unwanted harmonics [5][23].

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

$$Power\ Factor = \cos\theta\ \frac{I_{1,rms}}{I_{rms}} \tag{2.4}$$

The current and voltage waveforms relationship with PF and THD are showed with Figure 2.1. PF is distorted with phase difference between current and voltage. And THD occurs because of non-linear load [1].

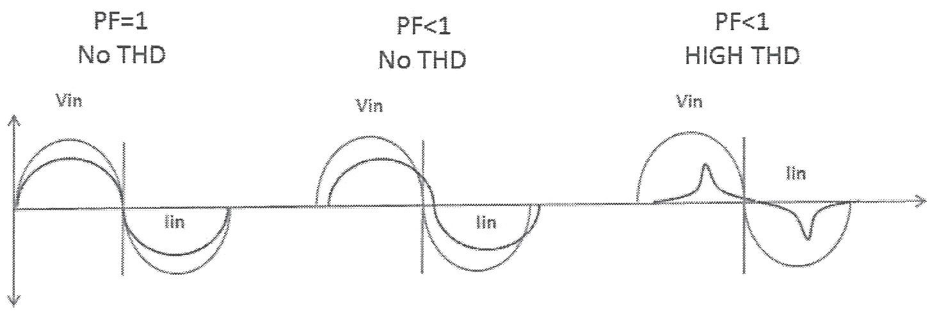


Figure 2.1: The relation between input current and input voltage

Power factor correction circuits shape the input current and maximize the real power from mains with reducing the peak and RMS current and eliminating phase shift. While international standards (IEC/EN 61000-3-2) dictate mandatory power factor correction levels for input powers above 25W, the new Energy-Star directive for solid-state lighting requires a power factor greater than 0.9 for power levels even above 3W [23][24]. And also get rid of harmonics minimizes the interference between devices which powered from the same source.

There are two common methods for optimizing power factor and THD. One of them is active power factor correction (PFC) method. It uses a switch mode boost converter with a PFC controller. This is the most popular method for PFC used in today's power supplies. And the other mode is passive PFC. Passive PFC is used for circuits that the size and weight not problem, because of using big inductor with the active circuit [22]. The Passive PFC technique is shown with Figure 2.2.

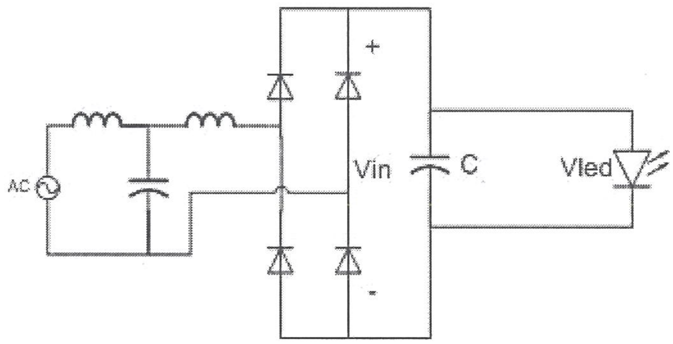


Figure 2.2: Passive PFC technique

The choice of topology is based on efficiency and power requirements. Most of PFC applications use Boost topology. Despite of the good advantages of Boost converters, the major disadvantage is having two different stages for PFC. Since efficiency is decreasing and components, size and cost are increasing. Two stage flyback PFC is shown in Figure 2.3.

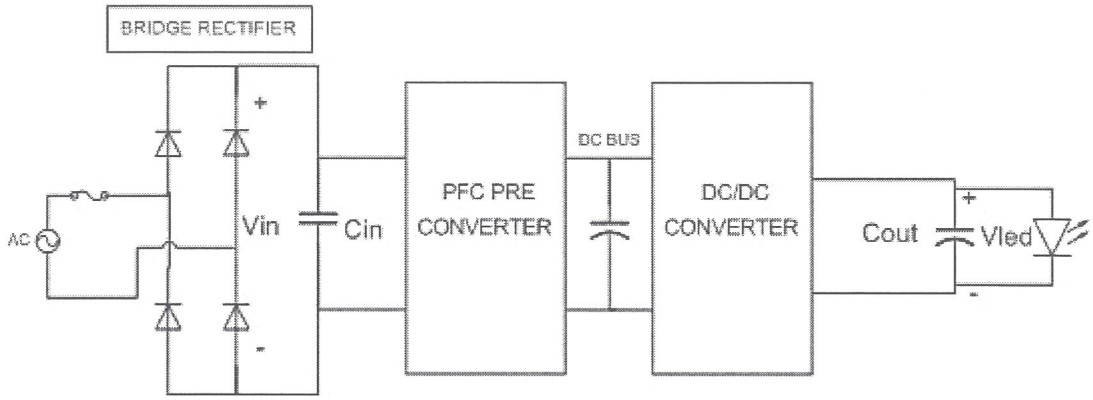


Figure 2.3: Two Stage Flyback Converter

The single stage flyback converter is a popular solution to achieve high efficiency, high power factor and low harmonic distortion with low cost. A single stage flyback converter with active PFC is shown in Figure 2.4. Due to power factor correction circuit, input current follows the input voltage and consequently the theoretical input current is sinusoidal and in phase with input voltage [7][8].

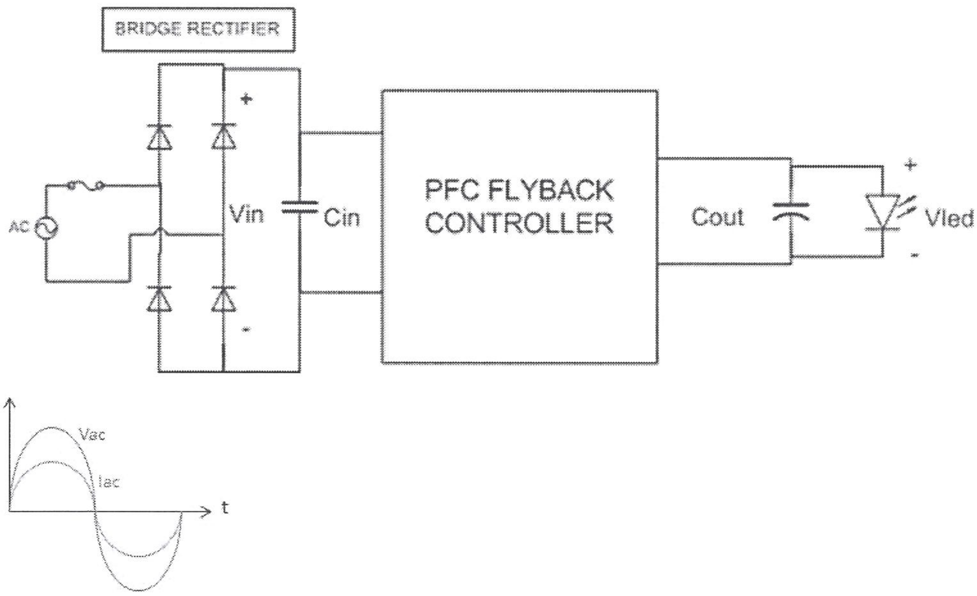


Figure 2.4: Single Stage Flyback Converter

2.1 Conduction Modes For Flyback Converter

The energy transfer modes for Single Stage Flyback converter are continuous conduction mode (CCM), discontinuous conduction mode (DCM) and critical conduction mode (CRM) that converter works at boundary between CCM and DCM [25]. The main difference between these modes is transfer mode of the energy, primary to secondary. These modes have pros and cons relative to each other. With Figure 2.5 the inductor current of the all conduction modes are showed [22].

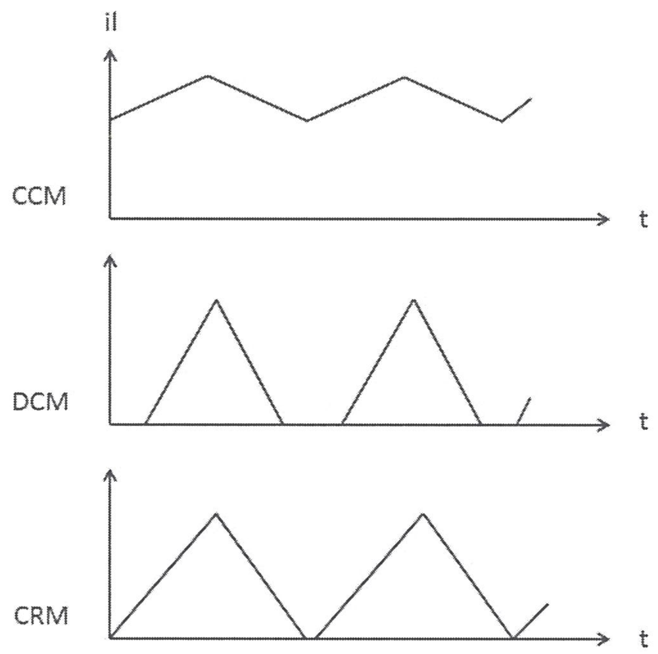


Figure 2.5: The inductor current waveforms of the conduction modes

LED lighting converters generally use flyback topology operated in Critical Conduction Mode or Discontinuous Conduction Mode. The Critical Conduction Mode is also called Transition Mode or Boundary Mode. In CRM, the power switch turns on instantly when the secondary current of the flyback converter decreases to zero [26]. With the features of zero current switching and lower peak current than DCM, CRM is the preferred conduction method for medium power applications [3][23].

2.2 CRM for Flyback PFC Converter

For the medium power applications, CRM is preferred operating method for Flyback PFC converters [27]. The main advantages are lower peak primary current and zero current switching. Conduction losses minimized by the lower peak primary current and switching losses minimized by the zero current switching [23][28]. Figure 2.6 shows the current waveforms of the CRM flyback PFC converter.

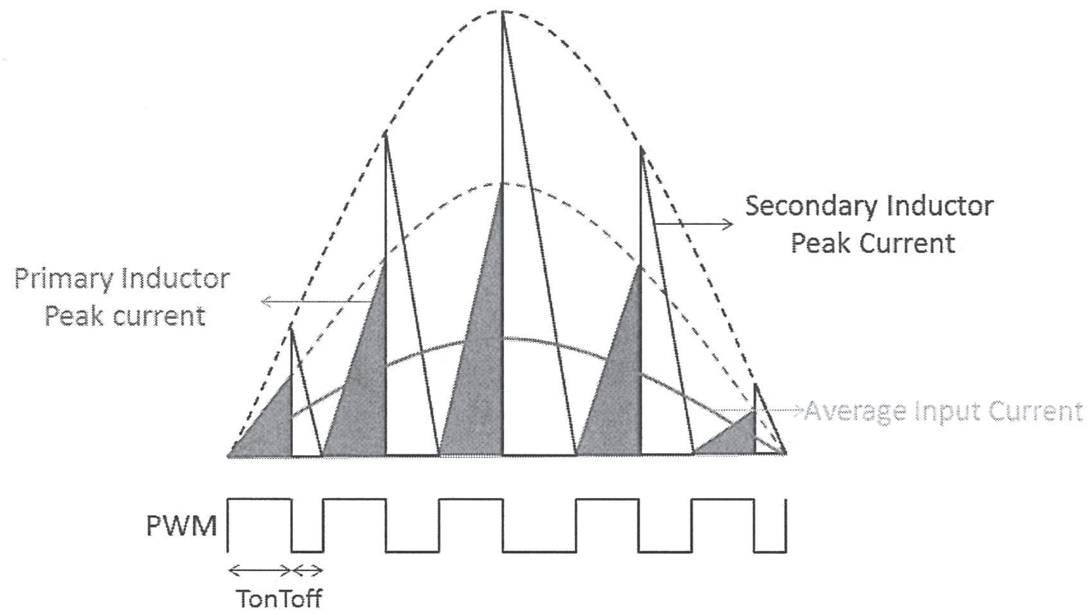


Figure 2.6: The current waveforms of the CRM flyback PFC converter

The main idea of the critical conduction mode is like this; for each switching period, the inductor current starts from zero. When the switching component of the converter is turned on for a constant time, the peak inductor current is proportional to input voltage [23]. As a result of constant on time and variable switching frequency, CRM flyback PFC controller have a high power factor but do not have a lower harmonic distortion.

2.3 Constant On Time Control Method For CRM

There are several control methods for CRM flyback PFC converter. These are current mode control, hysteretic control, constant-frequency control, constant-on time control, average current mode control. One popular control method for CRM is Constant-On-Time (COT) control and with this method only a voltage control loop is needed. Only output voltage is monitored with this method. A voltage error is calculated by forming the difference between output voltage desired and output voltage actual. Because of the only control parameter is output voltage, this method responds slowly to input changings. The switch turns on for a predefined period and then turns off till the inductor current reaches zero [14].

With COT control scheme, the input peak current automatically follows the input voltage in a line cycle. Generally, for COT controlled boost PFC converter, the theoretical average input current is sinusoidal. But for a flyback PFC, the average input current is also related to the duty cycle, which will causing to low PF and high THD [29]. The duty ratio is a proportional to relation with the input and output voltage. The other disadvantage of CRM is that at the zero crossing of the AC line. While the constant on time, the instantaneous input voltage is not large enough to store sufficient energy in the inductor. The zero crossover distortion, hence, also increases the THD and decreases the PF of the converter [3].

The function block diagram of the constant on-time controlled PFC is shown in

Figure 2.7. It utilizes a ramp generator. A voltage ramp V_{RAMP} with a constant slope S_{RAMP} will generate with a ramp generator. When input the ramp voltage V_{RAMP} reaches the feedback node voltage V_{COMP}, the PWM signal is reset and the power switch Q_1 is turned off. The feedback node voltage V_{COMP} is generated by comparing the feedback signal V_{FB} and reference voltage V_{REF} through an error-amp OTA. If the OTA bandwidth is controlled to be lower than the input voltage frequency, the output V_{COMP} will look like a DC voltage with very low ripple [23]. Consequently, the primary peak current will be a sine-looking wave with same phase with the input voltage, with high power factor.

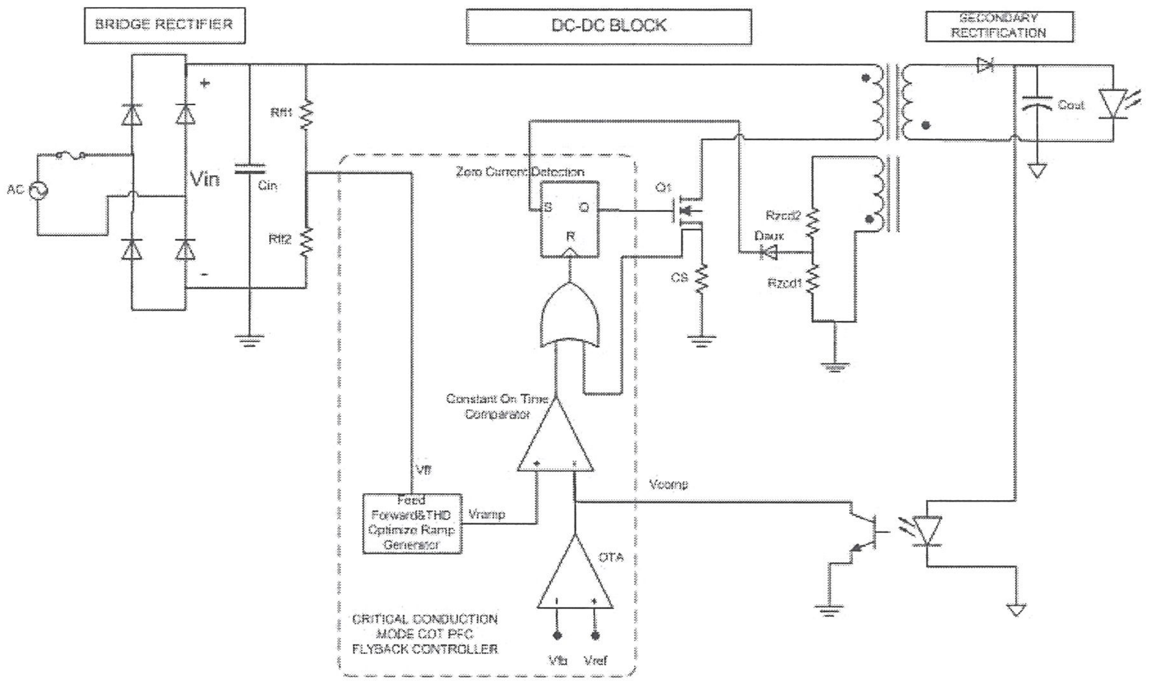


Figure 2.7: The function block diagram of the COT CRM flyback PFC converter

For the constant on-time control, the input voltage feedforward compensation is used to keep V_{COMP} feedback voltage almost unchanged under different input voltages. Figure 2.8 is the function block diagram of the Ramp generator in most common PFC distortion compensation schemes. OTA's output charge the capacitor C_{RAMP} until the equality of voltage V_{RAMP} and feedback voltage V_{COMP} [23].

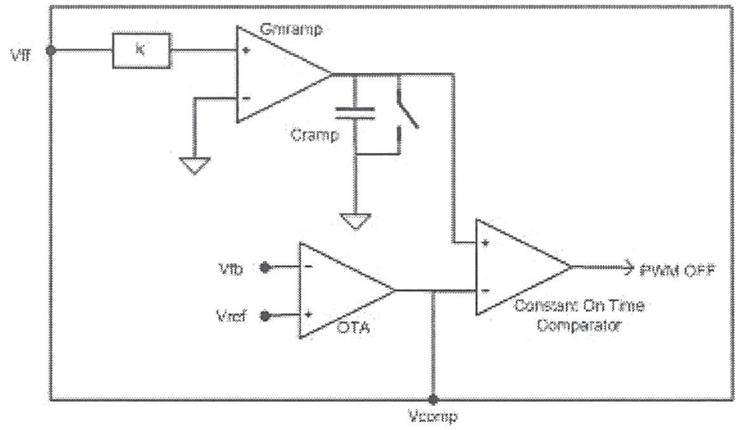


Figure 2.8: The function block diagram of the ramp generator

The constant on-time T_{on} can be derived from the following equations.

$$P_{in} = \frac{1}{4} V_{in_{pk}} I_{in_{pk}} \frac{T_{on}}{T_s} \tag{2.5}$$

$$I_{in_{pk}} = \frac{V_{in_{pk}}}{L_{PFC}} T_{on} \tag{2.6}$$

$$P_{in} = \frac{1}{4} \frac{{V_{in_{pk}}}^2}{L_{PFC}} T_{on} \frac{T_{on}}{T_s} \tag{2.7}$$

$$T_{on} = \frac{4\, P_{in}\, L_{PFC}}{{V_{in_{pk}}}^2 \frac{T_{on}}{T_s}} \tag{2.8}$$

The T_{on} is implemented by a constant current charging a capacitor till V_{COMP} threshold voltage is reached. Therefore, the T_{on} is a function of V_{COMP}. Hence, the V_{COMP} can be derived from below equation. R_{ff} is the rate of feed-forward voltage to input voltage [23].

$$T_{on} = \frac{C_{ramp}.V_{comp}}{I_{ramp}} \tag{2.9}$$

$$V_{comp} = \frac{4\,P_{in}\,L_{PFC}}{V_{in_{pk}}{}^{2}\,\frac{T_{on}}{T_s}} x \frac{I_{ramp}}{C_{ramp}} \tag{2.10}$$

$$I_{ramp} = k\left[V_{in_{pk}}\sin(wt)\,R_{ff}\right]^2 GM_{ramp} \tag{2.11}$$

$$R_{ff} = \frac{R_{ff1}}{R_{ff1} + R_{ff2}} \tag{2.12}$$

$$V_{comp} = \frac{8\,P_{in}\,L_{PFC}GM_{ramp}R_{ff}{}^{2}sin^2(wt)}{D(t)\,\pi^2 C_{ramp}} \tag{2.13}$$

2.4 Proposed Control Scheme

With respect to Figure 2.6, the average input current of primary side and duty cycle of CRM flyback PFC converter can be derived as;

$$I_{in}(t) = \frac{V_{in_{pk}}}{2\,L_{PFC}} T_{on} D(t)\sin(wt) \tag{2.14}$$

$$D(t) = \frac{1}{1 + ({}^{V_{in_{pk}}}/_{N.V_{out}}\;\sin(wt))} \tag{2.15}$$

From input current equation, if the on-time T_{on} of the switching component is kept unchanged, the input current I_{in} and input voltage V_{in} still have the relation with duty ratio D(t).

$$T_{on} = \frac{C_{ramp}V_{comp}}{k\,V_{in_{pk}}R_{ff}GM_{ramp}} \tag{2.16}$$

$$I_{in}(t) = \frac{V_{comp}C_{ramp}D(t)}{2L_{PFC}kR_{ff}GM_{ramp}} x\sin(wt) \tag{2.17}$$

For optimizing THD and Power Factor, a simple forward winding is added to primary of the Flyback transformer. $\sin(wt)$ signal which is the output of the added winding is injected to V_{COMP} voltage. By this kind of signal dependent pulse injection strategy, the PF and THD of the CRM flyback PFC converter is improved significantly.

Figure 2.9 is the function block diagram of the constant on-time PFC control with proposed control scheme. After adding a winding to primary side, the new on time T_{on_2} and the new input current equations are shown below. With this method, T_{on} is as well changing cycle-to-cycle according to the input voltage of the flyback. M represents the fractional factor of the added $\sin(wt)$ signal through this injection path. This fractional rate is depended on system requirement and specification. If one increases this rate, the input current will be more sinusoidal, but, the voltage on the controller pin should not rise above the controller pin threshold voltage to keep reliability intact.

$$T_{on_2} = \frac{C_{ramp}(V_{comp} + (\frac{2}{\pi} V_{in_{pk}} M \sin(wt))}{k V_{in_{pk}} R_{ff} G M_{ramp}} \tag{2.18}$$

$$I_{in}(t)_2 = I_{in}(t) + \frac{C_{ramp} V_{in_{pk}} M\, D(t) \sin^2(wt)}{k L_{PFC} R_{ff} G M_{ramp}\, \pi} \tag{2.19}$$

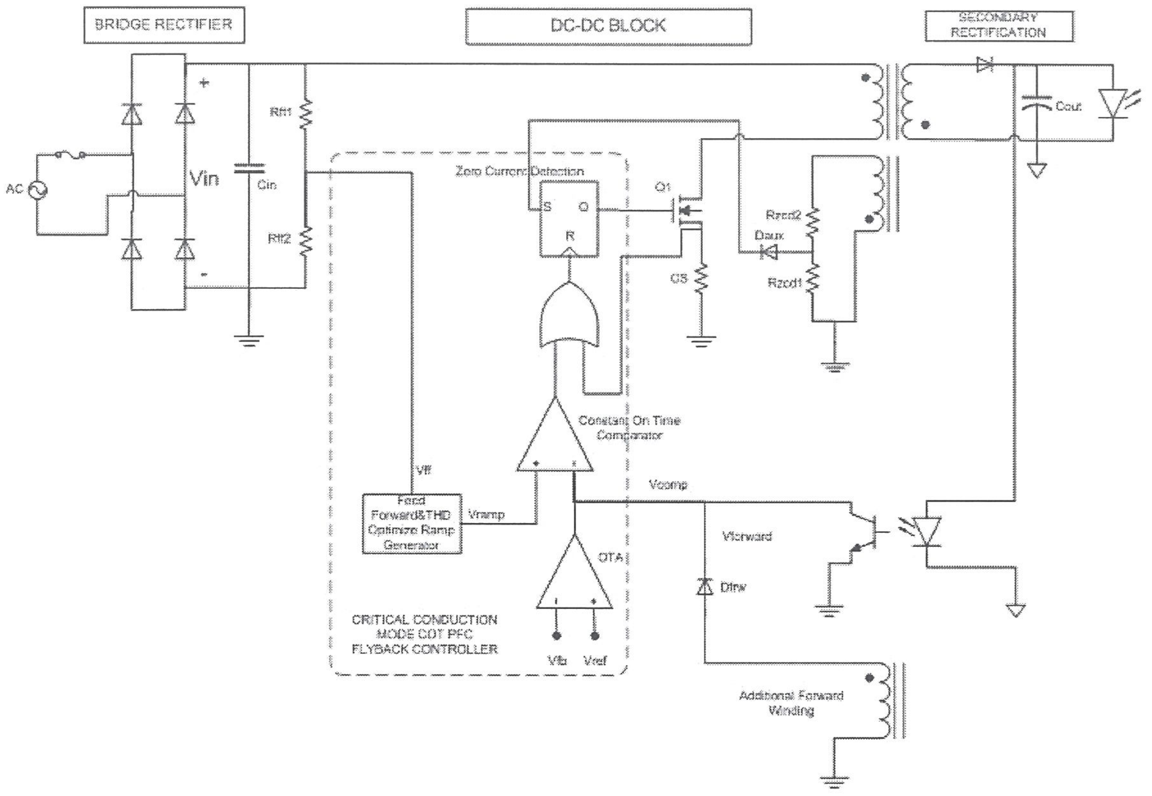
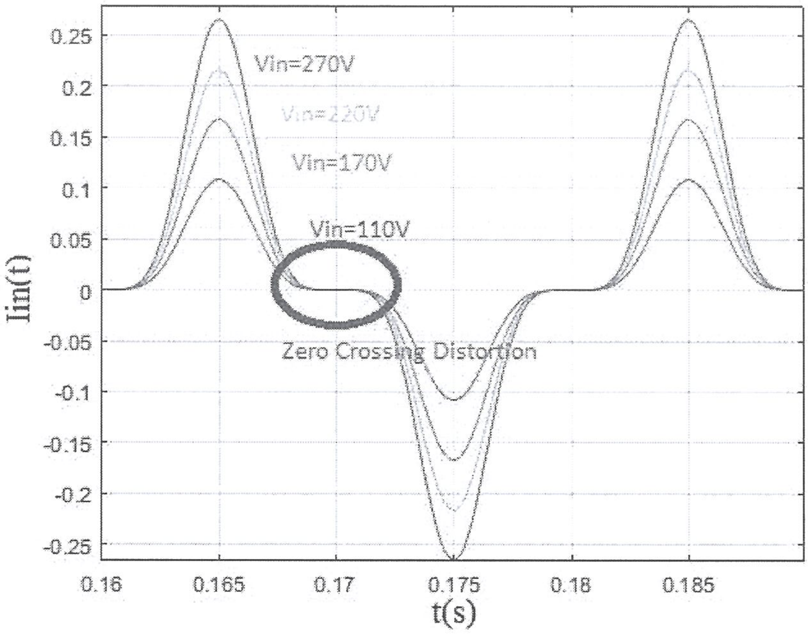
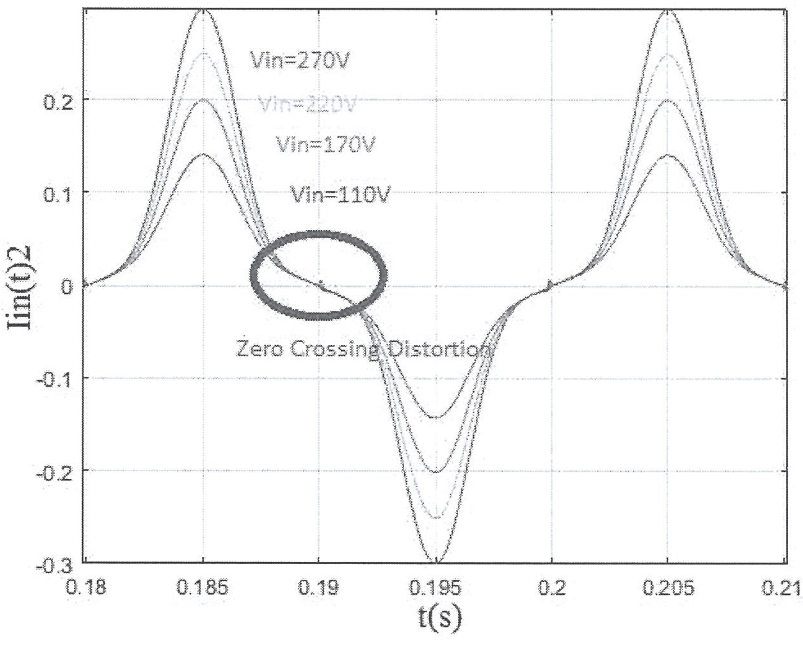


Figure 2.9: The function block diagram of the constant on-time PFC control with proposed control scheme

Matlab waveforms of $I_{in}(t)$ and $I_{in}(t)_2$ are illustrated in Figure 2.10. The difference in the source current waveforms is quite visible. Figure 2.10-a shows the regular PFC controller current waveform whereas Figure 2.10-b shows the waveforms for the proposed primary winding injection technique.



a)



b)

Figure 2.10: Input current MATLAB waveforms of a) Without winding b) With winding

CHAPTER III

DESIGN AND ANALYSIS OF HIGH POWER FACTOR AND LOW THD CONVERTER FOR LED LIGHTING

Two converter prototypes are designed with CRM flyback PFC topology to verify the performance of the proposed control technique.

Two prototypes are built for comparison of the two control schemes; first the conventional PFC control, and the second is the proposed added winding injection strategy for a standard CRM flyback converter. Both of the prototypes had been built of the same power circuit subcomponents, as shown in TABLE 3.1.

Table 3.1: PROTOTYPE'S SPECIFICATION

Parameters	Value
AC Input Voltage V_{AC}	220-240V
AC Input Frequency	50-60Hz
Output V_{out} /I_{out}	30V/1.05A
Estimated Efficiency	88%
Estimated max average input power	35,8W
Transformer Core	RM6

For the both prototypes, Richtek RT7300 controller with active PFC critical conduction mode controller is used.

3.1 Design of CRM Flyback PFC Converter

After definition of the input and output conditions the transformer is designed. The ideal turn ratio of primary to secondary windings is defined with equation (3.1). V_{RO} is recommended to be within 90-130V by datasheet.

$$\frac{N_p}{N_s} = \frac{V_{RO}}{V_{out} + V_{frw}} = 3{,}91 \tag{3.1}$$

The ideal turn ratio of secondary to auxiliary windings is defined with equation (3.2). V_{DD_MAX} is recommended to be within 17-22V by datasheet.

$$\frac{N_s}{N_{aux}} = \frac{V_O}{V_{DD_{max}}} = 1{,}58 \tag{3.2}$$

Maximum on time is defined with equation (3.3). Some of the constants are given by datasheet.

$$t_{on_{max}} = \frac{\frac{1000}{f_{s_{min}}} - 1}{V_{RO} + \sqrt{2}V_{AC_{min}}} = 6{,}68uS \tag{3.3}$$

Primary side inductance, primary maximum peak current, secondary maximum peak current, minimum turn number of the primary winding are defined with below equations.

$$L_m = \frac{\frac{\left(t_{on_{max}}\sqrt{2}V_{AC_{min}}\right)^2}{4}}{P_{in_{max}} f_{s_{min}} 1000} = 1206uH \tag{3.4}$$

$$I_{ppq} = \frac{\left(t_{on_{max}}\sqrt{2}V_{AC_{min}}\right)}{L_m} = 1{,}7222A \tag{3.5}$$

$$I_{spq} = I_{ppq}\frac{N_p}{N_s} = 4{,}019A \tag{3.6}$$

$$N_{p_{min}} = \frac{I_{ppq} L_m}{B_{max} A_e 10^{-4}} = 40{,}95 \tag{3.7}$$

As a result of calculations, the following features are selected for the transformer.

Table 3.2: TRANSFORMER'S SPECIFICATION

Parameters	Value
Transformer Core	RM6
Turns Ratio of Transformer $N_P : N_S : N_{aux} : N_{FRW}$	40:10:7:4
Primary Inductance of Transformer L_m	1,2mH

The feed forward resistor divider ratio is determined with equation (3.8).

$$S_c = \frac{R_{ff1} + R_{ff2}}{R_{ff1}} = 196{,}16 \tag{3.8}$$

Mosfet and diode are determined by below calculations.

$$V_{ds_{max}} = V_{rrm_{max}} + V_{clamp} = 489{,}4V \tag{3.9}$$

$$I_{ds_{max}} = I_{p_{pq}} = 1{,}7222A \tag{3.10}$$

$$V_{do_{max}} = \frac{V_{rrm_{max}}}{\frac{N_p}{N_s} \cdot V_{o_{ovp}}} = 115{,}9V \tag{3.11}$$

$$I_{do_{max}} = I_{o_{max}} = 1{,}05A \tag{3.12}$$

Table 3.3: MOSFET AND DIODE SELECTION

Parameters	Value
Mosfet	6A/800V
Bridge Diode	2A/1000V
Output Diode	10A/100V

With the definition of environmental components the converter is designed. Since dimming feature is a reason for choosing, secondary side dimmable current controller is added to designed circuit. For dimming feature Richtek RT8457 controller is used. This controller is selected due to isolation and efficiency advantages. Prototype is designed to comply with safety and EMC standards.

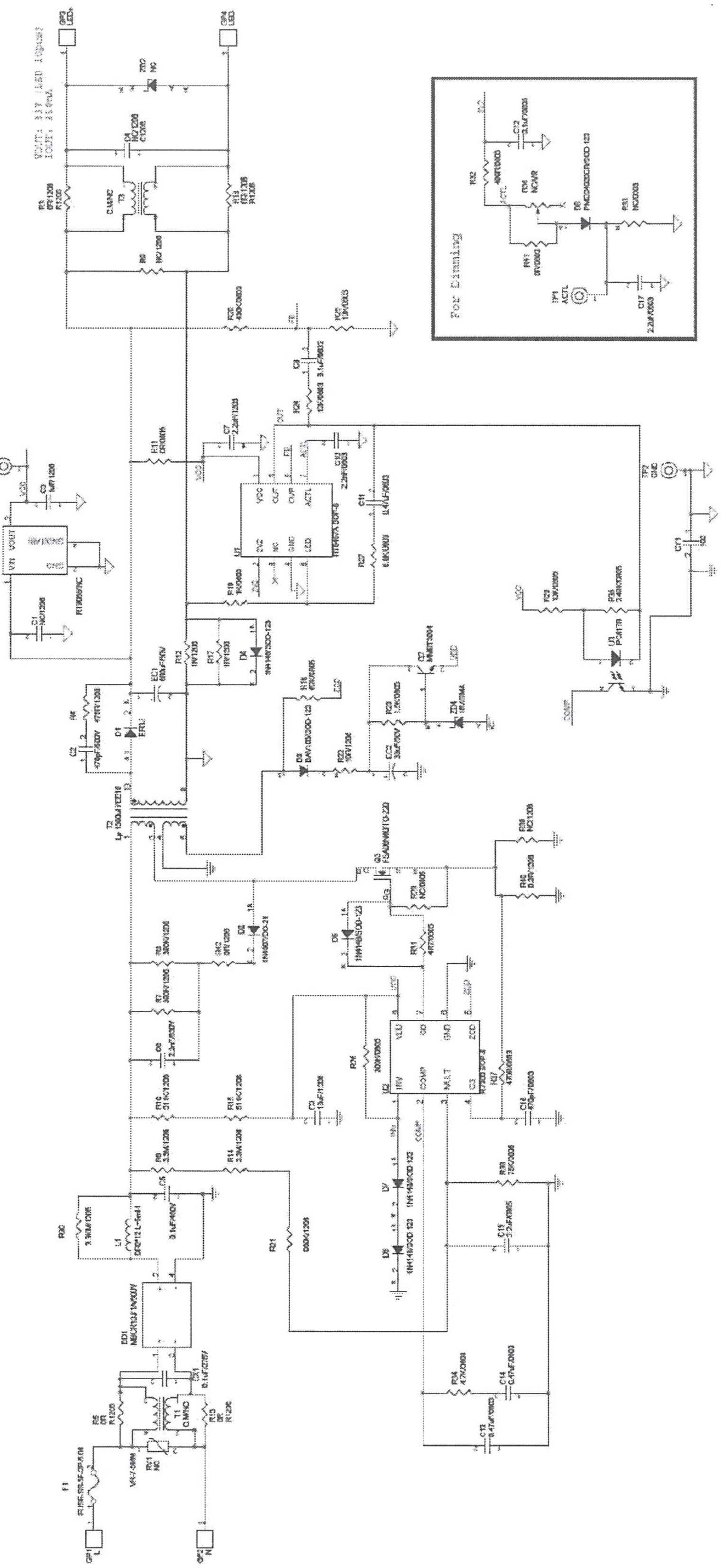


Figure 3.1: The schematic of the reference design [30].

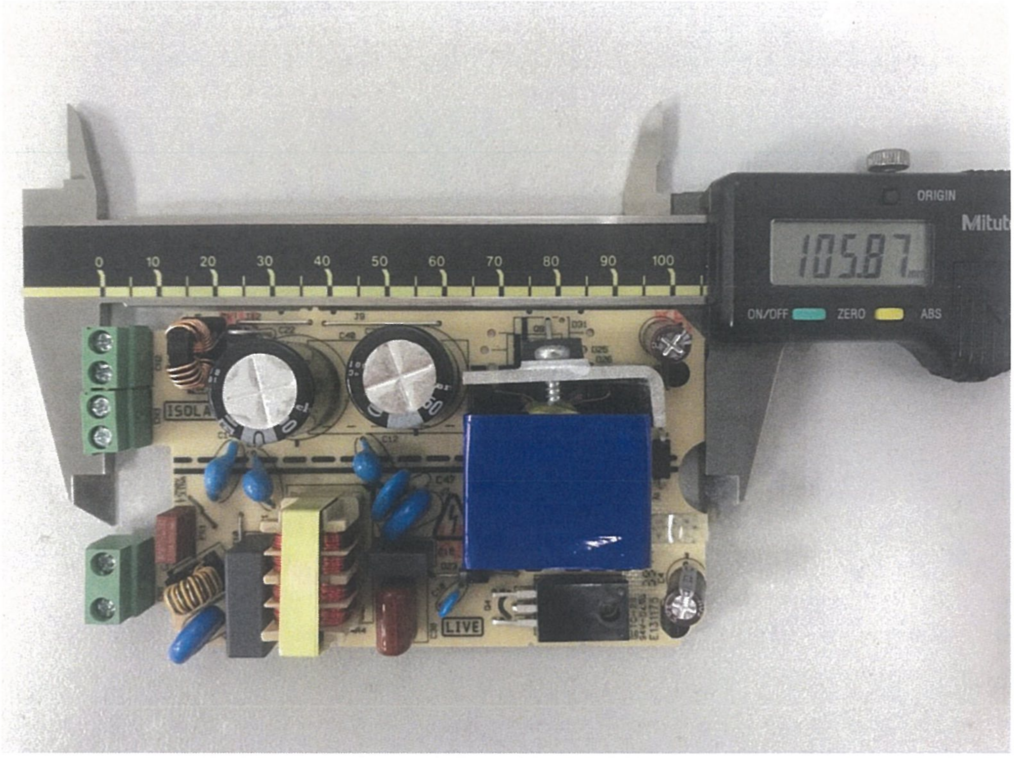


Figure 3.2: The top of the CRM Flyback PFC circuit

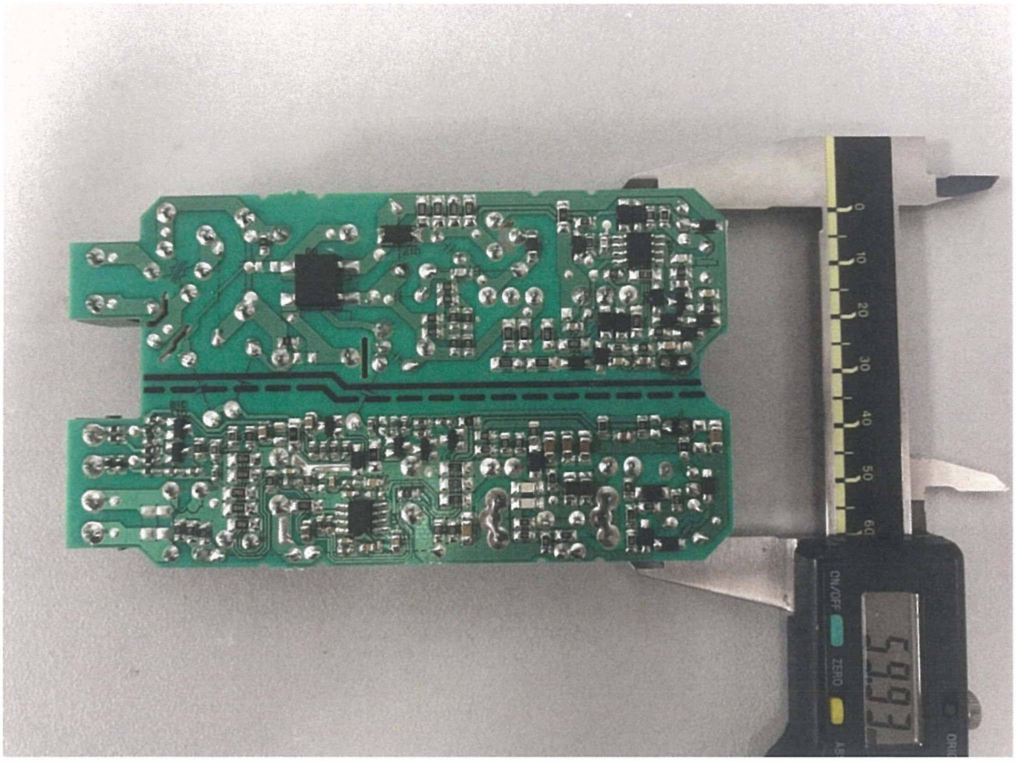


Figure 3.3: The bottom of the CRM Flyback PFC circuit

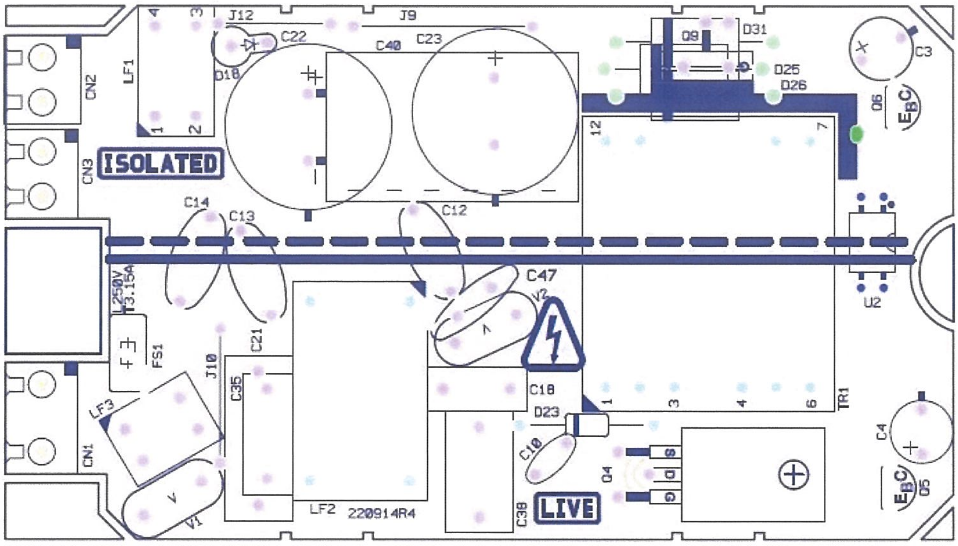


Figure 3.4: The top of the PCB Layout of the CRM Flyback PFC design

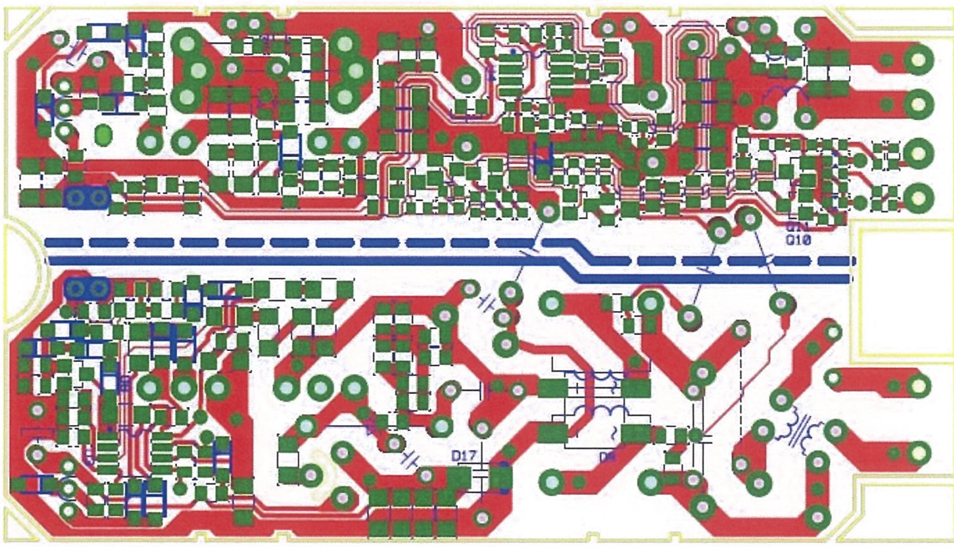


Figure 3.5: The bottom of the PCB Layout of the CRM Flyback PFC design

3.2 Experimental Results

With the classic constant on time controlled CRM flyback converter's and CRM flyback controller with the proposed forward winding scheme's measured rectified input voltage Vin and input current I_{in} waveforms are shown in Figure 3.6 and Figure 3.7.

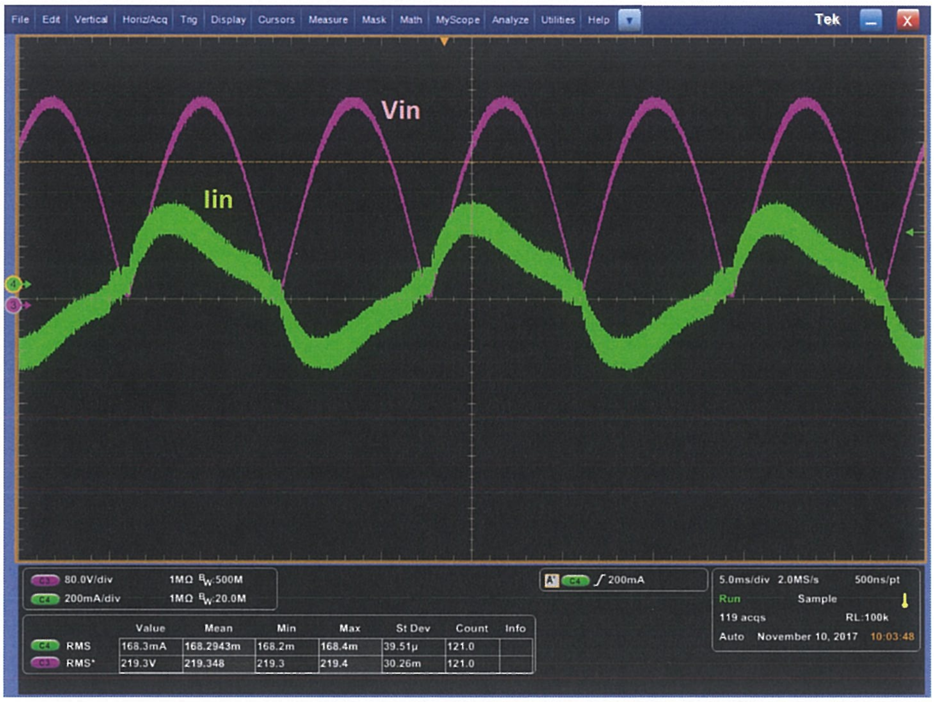


Figure 3.6: Measured input current and voltage waveforms of classic CRM flyback controller

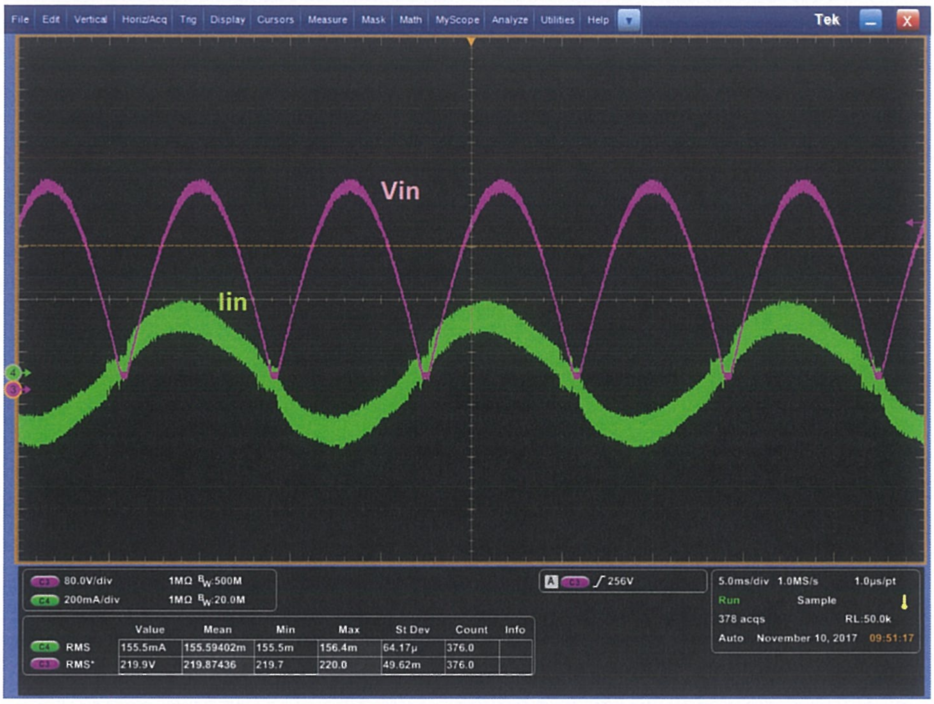


Figure 3.7: Measured input current and voltage waveforms of CRM flyback controller with the proposed forward winding scheme

It can be observed that the input current waveform with the forward winding scheme is better than the classical approach. The input current is clearly more sinusoidal with the proposed circuit. Also input voltage and primary coil currents of the corresponding systems are shown in Figure 3.8 and Figure 3.9.

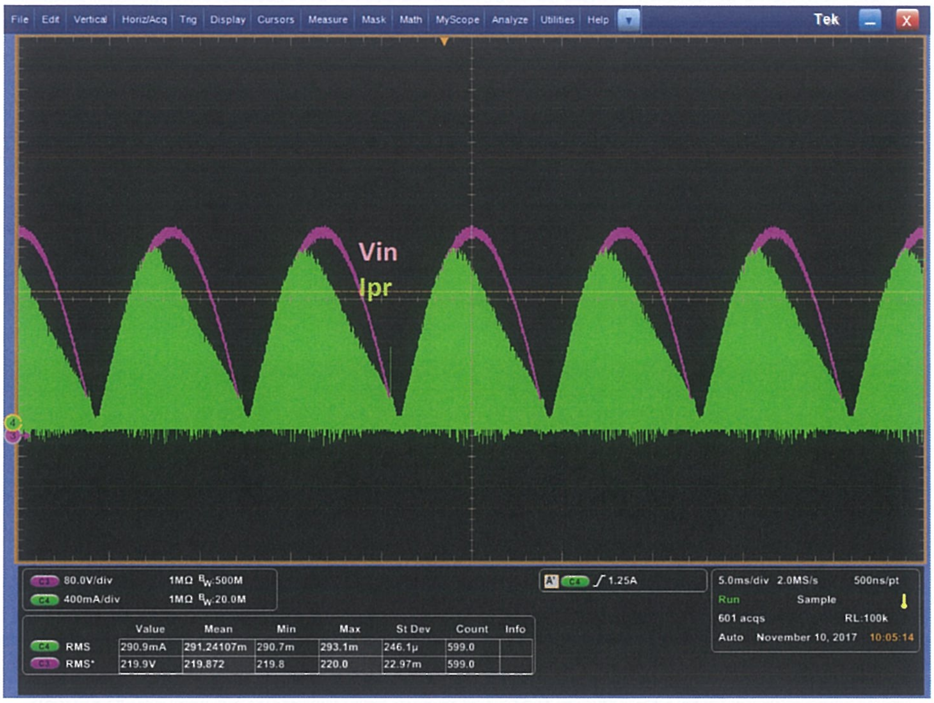


Figure 3.8: Input voltage V_{in} and primary current waveforms without the proposed forward winding scheme

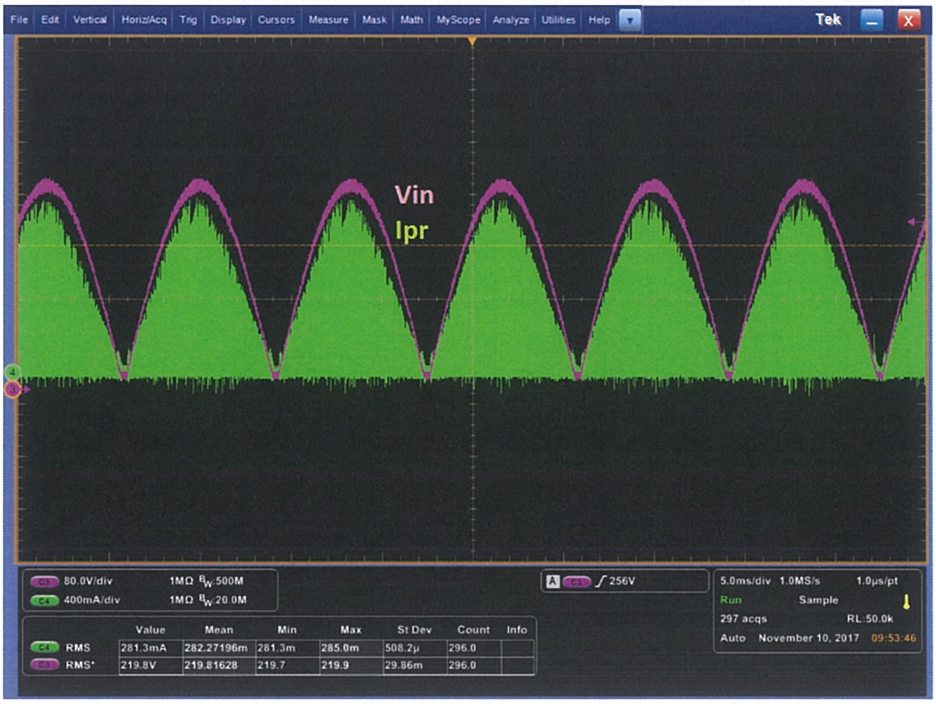


Figure 3.9: Input voltage V_{in} and primary current waveforms with the proposed forward winding scheme

The measured power factor and the total harmonic distortion comparison of the both schemes at different voltage swings are shown in Figure 3.10 and Figure 3.11. Input current harmonic levels are also shown in Figure 3.12.

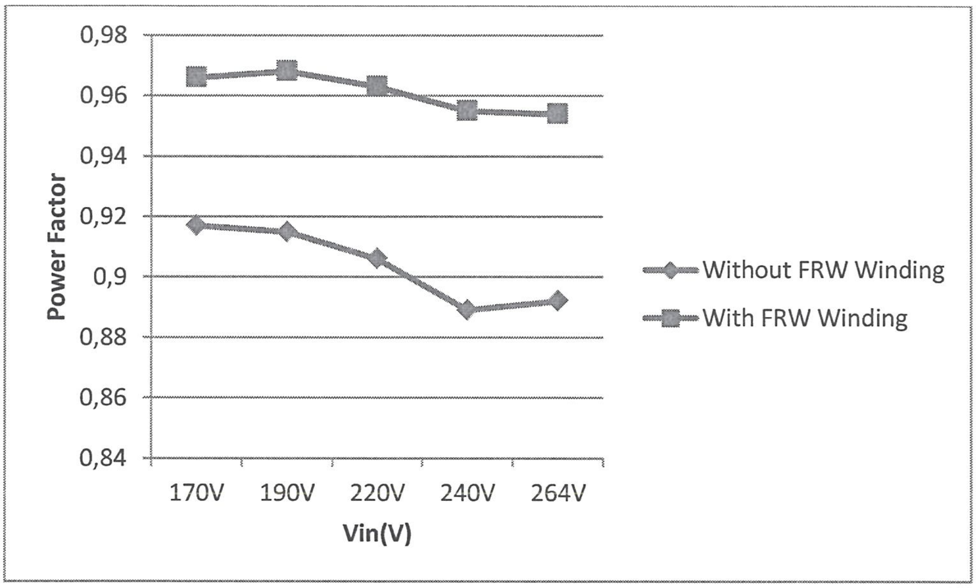


Figure 3.10: PF comparison at different input voltages – Input voltage vs Power Factor

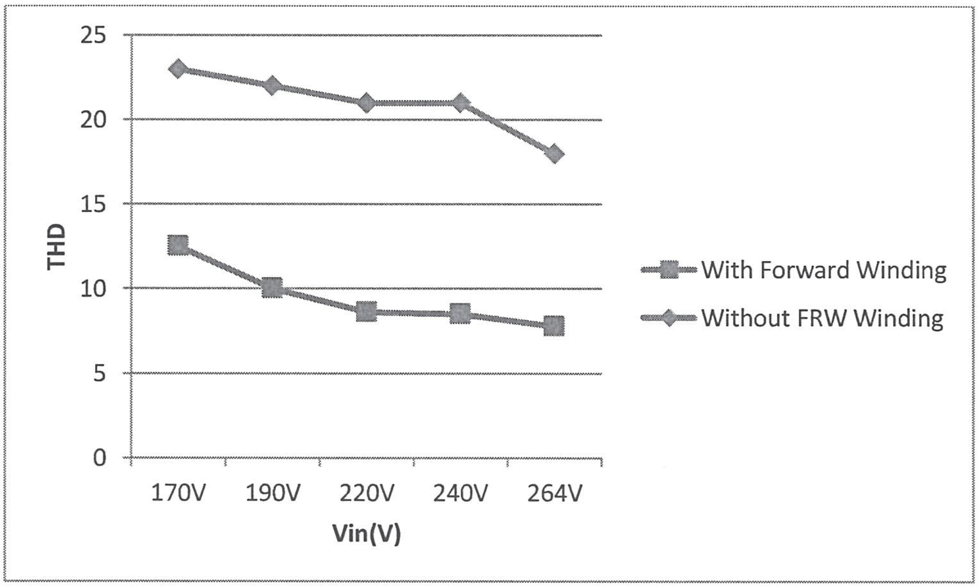


Figure 3.11: THD comparison at different input voltages – Input voltage vs Power Factor

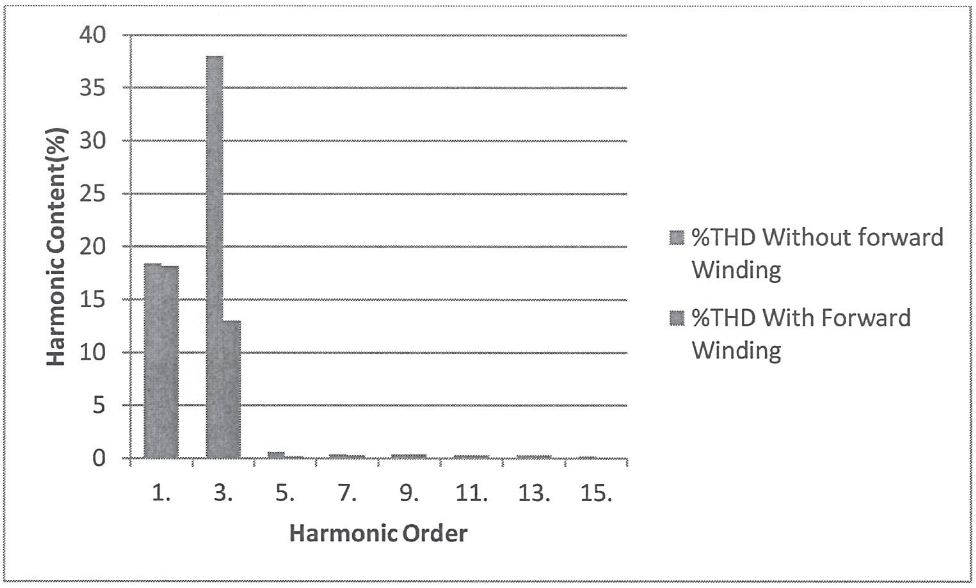


Figure 3.12: Input current harmonics at 220V AC Input

In order to verify the performance of the critical conduction mode flyback PFC and critical conduction mode flyback PFC with proposed control scheme, a converter is designed to provide constant current 1050mA and 30V maximum output voltage. With this design, firstly the power factor and THD performance verified for classical CRM flyback PFC converter. Then the performance difference in added forward winding state is also seen.

CHAPTER IV

CONCLUSION

Since LED market expands rapidly and solid-state lighting applications must be used with the appropriate converter, the topology selection of power supply is too important. For LED lighting applications, CRM flyback PFC is a popular choice because of efficient and low cost solutions. Besides traditional CRM flyback PFC converter has a good power factor and harmonic distortion, for some applications better performance can be sought.

It is difficult to get better performance with simple techniques because of difficult adjustment of the feedback and control cycle. If you use different methods like two stages PFC, it is easy but not economical. So if you want to improve the performance, doing the improvement with Single Stage PFC Converter is the best way. And without any application, it is difficult to see the distortion with electronic simulation because of the circuit components can not be simulated as in practice. So you must work with an application circuit.

The study presented a new CRM Flyback driver approach of added forward winding to improve total harmonic distortion and power factor. The main benefit of the proposed method is its simplicity and improvement of input current PF and THD compared to traditional constant on time controlled CRM flyback PFC converters. The theoretical analysis is done with Matlab simulation and supported with the controlled experimental results resulting in a lead study for future convertors.

The main focus of thesis is improving the power factor and total harmonic distortion of the traditional constant on time controlled CRM Flyback PFC Converter with improving the control loop of the controller. There are also other control techniques for CRM Flyback Converter. In the future works, improvements can be tried with the other control methods.

APPENDIX A

MATLAB CODE FOR PLOTTING INPUT CURRENT

```
%Mustafa Kavcı
%MATLAB code for plotting input current of CRM flyback PFC controller



t=0:10e-5:1;

for i = 1:4
    for j = 1 : 10001
        %%%%% Related Variables %%%%%%
        f = 50;
        w = 2 * pi * f;

        %%%%% D(t) Variables %%%%%%%%%
        V_pk = [110*sqrt(2), 170*sqrt(2) , 220*sqrt(2), 270*sqrt(2)];
        N = 0.1923;
        V_o = 30;

        D(i,j) = 1 ./(1+((V_pk(i)./(N*V_o)).*sin(w*t(j))));

        %%%%% K Variables %%%%%%%
        Cramp = 6.5e-12;
        k = 0.5;
        L = 1200e-6;
        Gm_ramp = 2.5e-6;
        Rff = 0.00777;

        K = (Cramp ./(k .*2 .*L .*Rff .*Gm_ramp));

        %%%%% V_comp Variables %%%%%%%%

        Pin = 35;

        %V_comp(i,j) = (2 .*Pin .* L .* Gm_ramp .*Rff.*Rff) ./ (Cramp
.*D(i,j));


        V_comp(i,j) = (8 .*Pin .* L .* Gm_ramp .*sin(w*t(j)) .*
sin(w*t(j)).*Rff.*Rff) ./ (Cramp .* D(i,j) .*pi .*pi);

        %%%%% I_in(t) Variables %%%%%%%%%

        m = 0.033;
```

```
          Iin_1(i,j) = (32 .* Pin .* V_pk(i) .* Rff .* Rff .*
(sin(w*t(j))^5)) ./ (pi^4);
          Iin_2(i,j) =  Iin_1(i,j) + (K * (V_pk(i)*2/pi) .*
(sin(w*t(j)) .* sin(w*t(j))) .* m .* D(i,j));



    end
end


for a = 1:4
   plot(t,Iin_1(a,:))
   hold on
   grid on
end
figure

for b = 1:4
   plot(t,Iin_2(b,:))
   hold on
   grid on
end
```

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VITA

Mustafa Kavcı was born in 1985 at Alaşehir. He received B.Sc. degree of Electronics and Communication Engineering from Yıldız Technical University in 2011. He is an Electronics Engineer with a focus on Power Electronics. He has experience to design drivers for consumer electronics, experience to analyze engineering problems, evaluate designs and recommend alternatives. He has good understanding of hardware product development, design for testability, identifying product failure modes and troubleshooting and verification. He has been working at Vestel Electronics R&D department as a Power Electronics Design Engineer.