PERFORMANCE ANALYSIS OF INTEGRATED SEPIC FLYBACK CONVERTER FOR POWER FACTOR CORRECTION DRIVE APPLICATIONS

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ABSTRACT

In this paper an isolated single-stage single-switch power factor correction driver for supplying light emitting diodes without electrolytic capacitor has proposed. The proposed LED driver, makes the switch turns on under zero current switching (ZCS) condition provided at a voltage less than its nominal voltage stress, and therefore, the switch capacitive turn-on loss decreases too much extent. The leakage energy is absorbed in the operation, to make no voltage spikes across the switch when the switch turns off. The operating principles of the proposed driver are illustrated in detail. Matlab simulink software has used to observe the results are presented to verify the theoretical analysis.

Keyword : - *Power Factor Correction Device, Zero current switching, Single stage converter, LED.*

1. INTRODUCTION

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 %. 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 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.

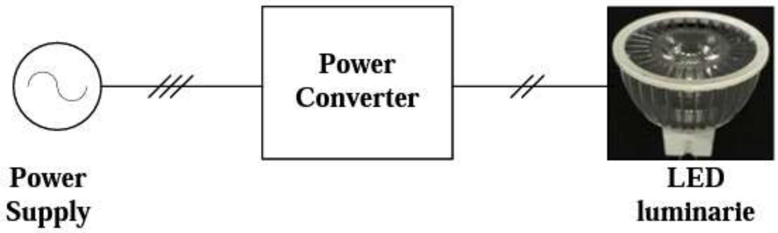

Fig-1: LED drive basic schematic

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.

In this paper, a new isolated single-stage single-switch PFC (S4 PFC) converter for LED driver applications is proposed, which is composed of a single-ended primary inductor converter (SEPIC) with a flyback converter and uses no electrolytic capacitors.

2. INTEGRATED SEPIC FLYBACK CONVERTER

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).

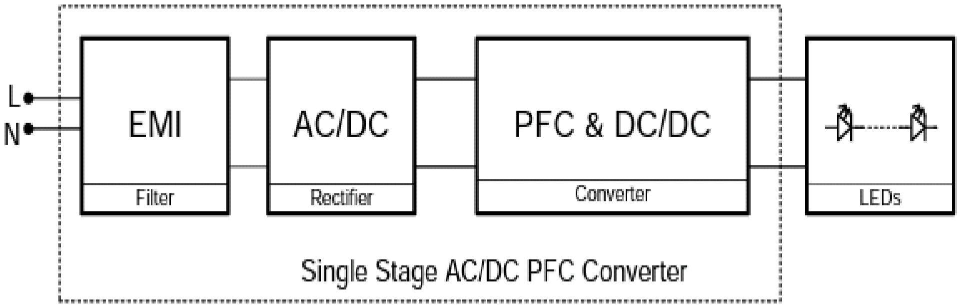

Fig-2: Basic schematic of single-stage PFC power converter for LED drive

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.

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.

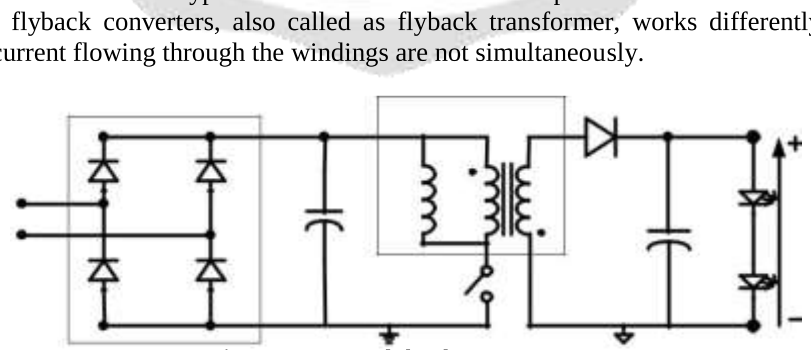

Fig-3: AC-DC Flyback converter

3. SINGLE-STAGE FLYBACK POWER-FACTOR-CORRECTION POWER SUPPLY

The proposed converter is illustrated in figure 4 with key element

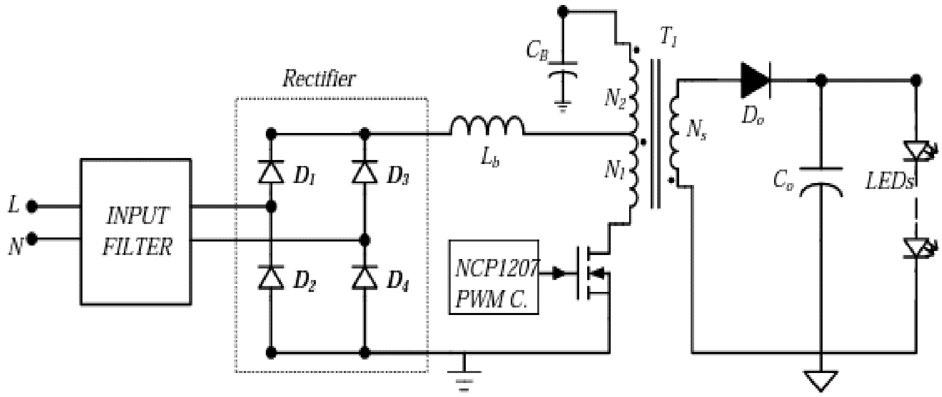

Fig-4: Single-Stage Flyback power-factor-correction front-end for HB-LED application

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.

3.1 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.

$$v_{in}(t) = \sqrt{2}V \sin \omega t \qquad (1)$$

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}).

$$i_m = i_{cb} + \frac{N_s}{N_2} i_{lb} \qquad (2)$$

Equation 2 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.

$$\Delta i_m = \frac{V}{L_m} \quad (3)$$

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

$$\Delta i_{LB} = \frac{v_{in} - (\frac{N_1}{N_p}) V_b \ \ DT_s}{L_b} \quad (4)$$

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;

$$V_{Coss} = V_b + \frac{N}{N_s} V_o \quad (5)$$

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:

$$\frac{di_{lb}}{dt} = -\frac{V_b + V_o \ N_2 \ N_s \ - v_{in}}{L_b} \quad (6)$$

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.

$$i_m = \frac{N_s i_s - N_2 i_{cb}}{N_p} \quad (7)$$

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.

$$i_s = \frac{N}{N_s} i_m + \frac{N}{N_s} i_{lb} \quad (8)$$

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

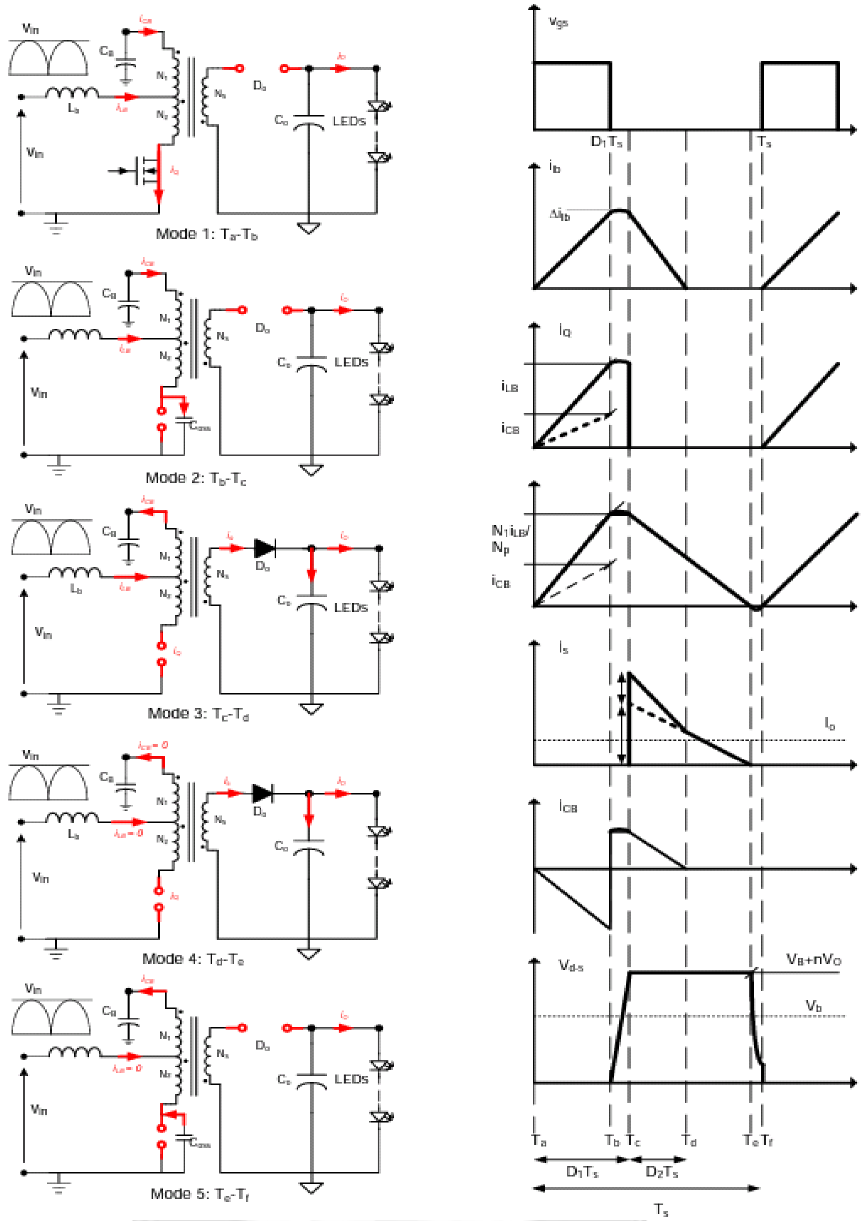

Fig-5: Operation modes for one switching period and characteristic waveforms for one switching period.

Here n denotes transformer transfer ration and V_{n1} denotes voltage on first part of primary winding of transformer.

4. SINGLE STAGE AC-DC CONVERTER FOR LED DRIVER

The proposed driver is a SEPIC converter (PFC cell) integrated with a flyback converter (dc–dc cell), both operating in discontinuous conduction mode (DCM). The elements of the SEPIC converter include L_{in}, L, D_1, C, and C_B ; and the flyback converter consists of a transformer T, two diodes D_2 and D_o, and an output capacitor C_o. Also, these two converters share the same switch S. C_B is the output capacitor of the PFC cell, so it acts as the bulk capacitor of the single-stage structure.

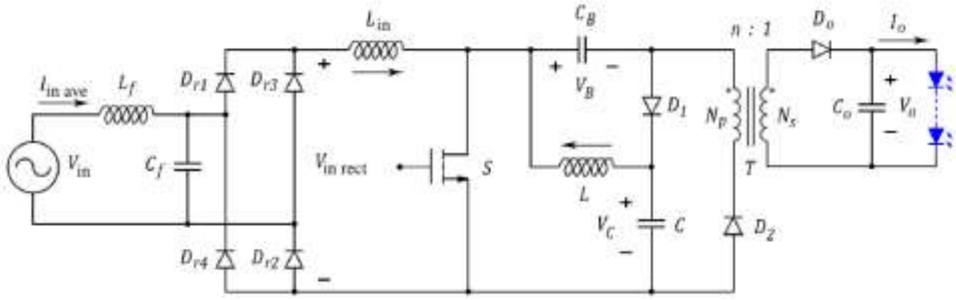

Fig-6: Circuit diagram of the proposed LED driver.

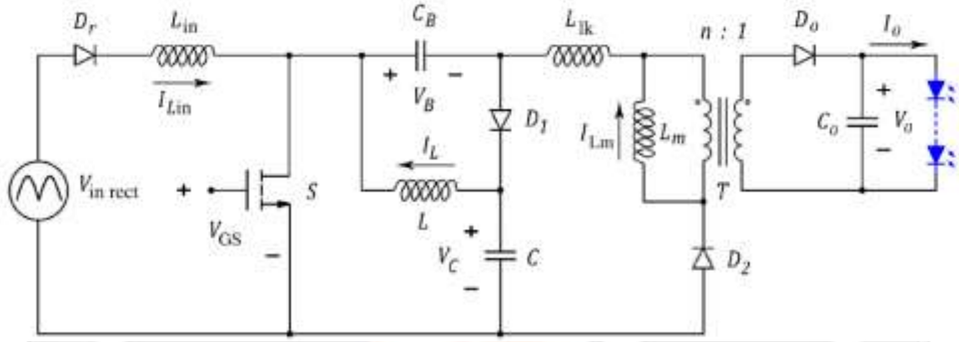

Fig-7: Simplified circuit diagram of the proposed LED driver

In the proposed driver, a near-unity PF is achieved by operation of input stage in DCM. As a result, the input current is discontinuous, and an extra LC filter is needed to filter out the high-frequency harmonics. For convenient explanation of the proposed driver operation, the circuit diagram shown in Fig. 6 is simplified. Fig. 7 shows this simplified circuit diagram. According to this figure, the input LC filter is omitted, and the ac input source and the bridge diodes are substituted by a rectified sinusoidal voltage source and a series diode D_r. Also, the transformer T is modeled by a magnetizing inductance L_m, a leakage inductance L_{lk}, and an ideal transformer.

The proposed LED driver has six operating modes during one switching cycle in steady-state condition. It is assumed that all semiconductor devices are ideal. Also, the capacitors C, C_B , and C_o are large enough that their voltages are constant, approximately. The switching frequency f_s is much larger than line frequency f_l, so the input voltage is constant during each switching period T_s. The transformer turns ratio is defined as $n = N_p/N_s$. The equivalent circuit diagrams and main waveforms of the proposed driver during a switching period are illustrated in Figs. 8. Before mode 1, it is assumed that all semiconductor devices are off, and the output capacitor provides the load current.

Mode 1 $[t_0 - t_1]$*:* This mode begins when the switch S turns on. The voltages $V_{in\ rect}$, V_C , and V_B are applied to the inductors L_{in}, L, and $L_m + L_{lk}$, respectively. Therefore, I_{Lin}, I_L, and I_{Lm} increase linearly from zero. Smooth increment of the currents through the inductors ensures zero current switching (ZCS) turn-on condition of the switch S and diode D_2. During this mode, the diodes D_1 and D_o are reverse biased. Time duration of this mode is equal to DT_s where D is the duty cycle of the switch. This mode ends when the switch S turns off.

Mode 2 $[t_1 - t_2]$*:* At the beginning of this mode, the switch S turns off and the diodes D_1 and D_o start conducting. By conduction of D_1, voltage across the switch is clamped to $V_B + V_C$. The voltage $V_C - nV_o$ is applied to the inductor L_{lk} inversely, and its current decreases until it reaches zero. In this way, the leakage energy is absorbed, and voltage spikes across the switch are eliminated. The time duration of this mode is too short, so I_{Lm} can be considered constant approximately. Therefore, the current difference between I_{Lm} and I_{Llk} is trans-ferred to output and the diode D_o turns on at ZCS. When I_{Llk} becomes zero, the diode D_2 turns off under ZCS condition, and this mode ends.

Mode 3 $[t_2 - t_3]$*:* During this mode, voltages across the inductors L_{in}, L, and L_m are equal to $-(V_B + V_C\ V_{in\ rect})$, $-V_B$, and $-nV_o$, respectively. Therefore, I_{Lin}, I_L, and $I_L$decrease linearly. Generally, each of these three currents can reach zero earlier; however, for proper operation, I_{Lin} reduces to zero first.

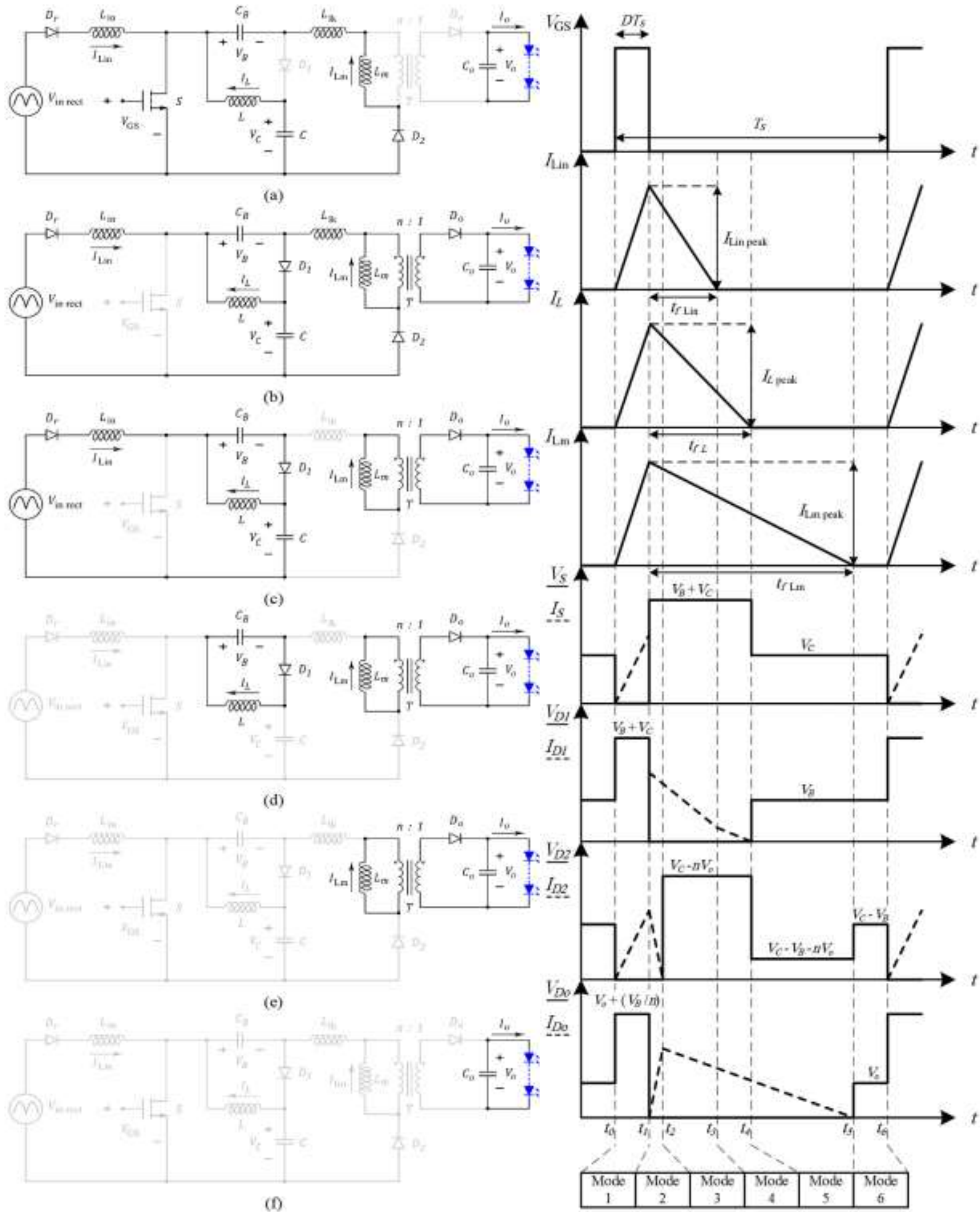

Fig-8: Equivalent circuit diagram of each operating mode. (a) Mode 1. (b) Mode 2. (c) Mode 3. (d) Mode 4. (e) Mode 5. (f) Mode 6 and Main waveforms of the proposed LED driver during a switching period

Mode 4 $[t_3 - t_4]$*:* During this mode, the diodes D_1 and D_o are conducting and the currents I_L and I_{Lm} are still decreasing. I_L becomes zero earlier and the diode D_1 turns off under ZCS condition.

Mode 5 $[t_4 - t_5]$*:* When the diode D_1 turns off, voltage across the switch decreases to V_C and remains at this voltage level until the end of next mode. During this mode, just the cur-rent I_{Lm} is decreasing and the currents of other inductors are zero. When I_{Lm} becomes zero, the output diode D_o turns off under ZCS condition.
Mode 6 $[t_5 - t_6]$*:* During this mode, all semiconductor devices are off and the output capacitor C_o provides the load current. Actually, this mode is the remaining time of the switch-ing cycle and continues until the switch turns on again. Since the switch turns on at a voltage less than its nominal voltage stress, the switch capacitive turn-on loss (which is proportional to square value of the switch voltage at turn-on time) decreases too much extent 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.

5. RESULTS AND ANALYSIS

The simulation of the proposed system using MATLAB has shown in figures from 8 to 11. The suppression of harmonics especially even harmonic has done using proposed method.

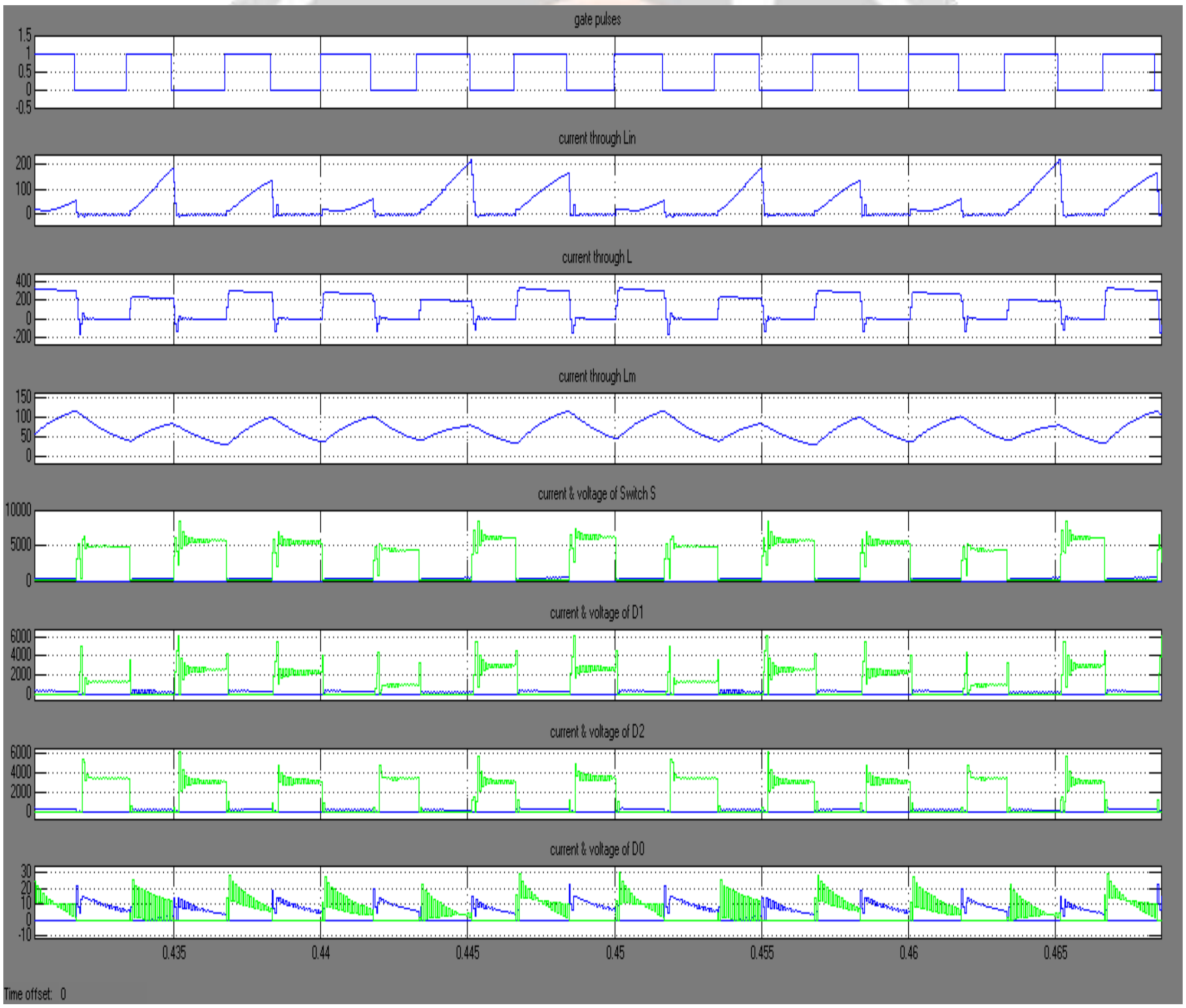

Fig-9: Simulation results of the proposed system showing gate pulses, current through Lin, L, Lm, current and voltage of D1, current and voltage of D2, current and voltage of D0.

The figure 9 represents the detailed analysis of results drawn using MATLAB simulink software. Simulation results of the proposed system showing results for gate pulses for the time period 0.43 to 0.46 seconds, current through Lin, L, Lm for the time period 0.43 to 0.46 seconds, current and voltage of D1, current and voltage of D2, current and voltage of D0 for the time period 0.43 to 0.46 seconds.

6. CONCLUSIONS

In this paper, prototype of S4 PFC LED driver without electrolytic capacitor has proposed which combines a SEPIC converter as PFC cell integrated with the flyback converter as dc–dc cell. In the proposed LED driver, the switch turns on at a voltage less than its voltage stress, so the switch capacitive turn-on loss decreases too much extent. Also, it turns on under ZCS condition and the leakage energy is recycled. Furthermore, voltage of the switch is clamped when it turns off and voltage spikes across the switch caused by leakage inductance are omitted. This means that switches with lower voltage ratings and lower on-resistances can be used. These features make to improve the proposed driver efficiency.

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