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Planar Flyback Transformer Design for PV Powered LED Illumination

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Abstract- Solar standalone LED lighting is becoming increasingly popular due to their economical, sustainability, simplicity and the low number of components. Designing of low volume and low weight driver decreases the price of LED drivers. Since the flyback converter has a low number of components, it is one of the most popular topologies for LED applications. The most important part of a flyback transformer or an inductor is the core. For the magnetic components, operation at high frequencies increases conductor losses due to skin and proximity effects. The use of planar transformers on printed circuit boards (PCB) can be an alleviate to this problem. With larger surface areas, planar transformers also provide better thermal performance than traditional wire-wound magnetic cores. Planar windings have different configurations. Optimal designing of core and winding reduce the losses of the transformer and inductors effectively. Therefore, this paper presents the design of a flyback planar transformer (PT) for photovoltaic (PV) powered LED illumination. The essential equations for designing of flyback PT are introduced and evaluated. The designed flyback PT was used in 50 W LED illumination driver powered by PV panel with a battery. In the proposed driver which was simulated by using MATLAB/Simulink program, the battery is charged via PV powered boost topology with Perturb Observation (P&O) MPPT method and an insulated H-bridge DC/DC converter.

Keywords Planar transformer, Flyback, LED, PV, MPPT.

1. Introduction

Conventional incandescent or fluorescent lamps that are still in use today require high energy and have low efficiency. In addition, this type of lighting has lower brightness than LED lighting. With its wide range of color options designed in LED lighting, it makes it attractive in building, environment and home lighting. The importance of LED lighting is increasing due to its higher brightness with lower energy and longer life.

The use of renewable photovoltaic (PV) systems is increasing in recent years. Since the solar energy is environment friendly and pollution free, it is the most favoured source of energy [1]. Therefore, the rate of use of PV systems has increased considerably in villages, districts and provinces where energy consumers are used in order to increase the use of renewable energy resources. Among the photovoltaic system applications, low-power electrical devices have a high rate. Among these low power devices are LED drivers that are used in home or street lighting and need direct form of DC electrical power [2]. A LED lamp device is turned off in daytime and lit at night, while the solar energy is generated at daytime [3]. In this context, solar panel-based multi mobile charger and home/street light applications have become quite common.

Flyback DC-DC converter which regulates DC voltage can be characterized by its low cost and simplicity. Therefore, they are becoming increasingly popular in low power applications. It has become an indispensable part of the flyback converter LED drivers that enable the input voltage to be converted to the desired output voltage. Two major factors affect a flyback converter. The first is the control circuit which generates the pulses (modulation techniques) of the static electric switch and the second is the design of the transformer. The inductor-transformer for these type converters play an important role during the switch's operating time and closing time. Energy handling capacity is a critical factor in the performance behaviour of these converters, therefore the design of the inductor- transformer is an active part of the overall design of the converter [4].

The switching frequencies have increasing depending on the application and with higher frequencies; we are able to achieve smaller size which will be very useful for high power densities. For high frequency switching operations, conventional wire magnetic materials are incompatible, leading to problems of increased high frequency loss caused by skin and proximity effects, in round conductors especially at frequencies above 100 kHz. And that's why we're moving to planar magnetic technology [5]. In [6] Planar core was compared to conventional one. On printed circuit boards (PCBs), it provides better performance, smaller in size, and easy to design because the windings are often repeatable. In addition, thinner and wider conductors help in reducing high-frequency losses due to skin and proximity effects.

The typical planar magnetic structure and a conventional wire wound magnetic structure are shown in Fig. 1.

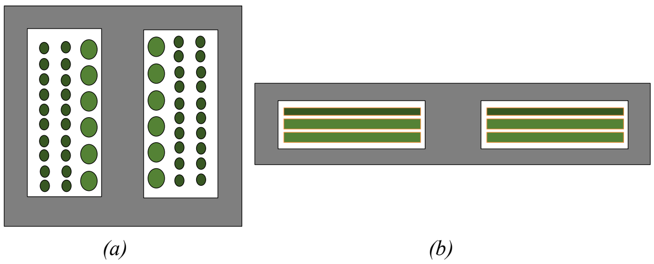

Fig 1. (a) conventional, (b) planar Flyback Transformer

The core of the planar device clearly has a lower profile than the conventional one. In addition, windings on the conventional device are stacked so that they are successively further from the center leg, i.e., windings are formed in the horizontal dimension while stacking in the vertical direction on the planar device instead for higher frequencies [7]. These differences in geometry of the core and winding provide an advantage over the traditional technology in many factors such as power density, ease of manufacturing and repeatability of magnetic device parameters.

The design of a flyback planar transformer for PV powered LED illumination is presented in this paper. The essential equations for designed flyback PT which was used in 50 W LED illumination driver were introduced and evaluated. The proposed driver was simulated by using Matlab/Simulink program and the related results are compared.

2. Proposed Solar LED Driver

The suggested solar LED driver is fed by a battery as seen in Fig.2. The battery of the proposed driver is charged with the energy obtained from the PV panel. Battery charging is carried out with MPPT applied through boost DC-DC circuit and insulated buck circuit.

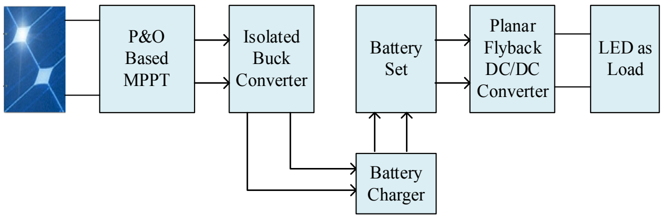

Fig 2. Block diagram of the suggested solar LED driver

The first part of the proposed solar LED driver circuit is the topics studied in detail in the literature. In addition, since the main emphasis of this study is the design of planar flyback transformer, the first part of the proposed circuit was not conducted in detail in the study. Battery charge control part of the proposed circuit consists of PV panel, MPPT based boost circuit and insulated buck circuit. The single-diode cell model [8] of the PV panel was used in the study. As the MPPT method, the P&O method is applied through the classical single-switched boost circuit, while the battery charge voltage regulation is done through the classical H-bridge DC-DC buck circuit [8]. The commonly used P&O MPPT technique can be considered the easiest to use. The flow chart and working principle of this method are given in detail in [9].

As stated before, since the main emphasis of this study is the design of planar flyback transformer, the design details of the planar flyback transformer which is given in Fig. 3 and used in the proposed solar LED driver circuit will be explained. Even though the study focused on planar flyback transformer design, the entire circuit of the proposed solar LED driver was modeled and designed in Matlab / Simulink environment, and the planar flyback transformer was used in this model.

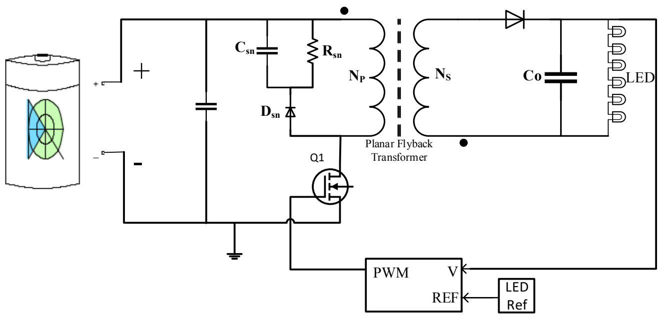

Fig 3. Planar flyback transformed based LED driver.

3. Design of Planar Flyback Transformer

3.1. Planar Transformer Basics

The basic construction of a planar transformer is very similar to that of the conventional transformer. Since the main operation of the transformer is still valid for the planer transformer, the structure and components become very similar in both the transformers. Just like a conventional transformer, this also has core, windings and insulation. The core can be made up of two halves, one at the top and one at the bottom. The cores of planar transformers are mostly manufactured by Ferroxcube [10,11]. Windings are placed In between these core windows. The windings are designed on PCB instead of Litz wire. PCB sizes vary according to the size of selected core. There are primary and secondary windings. There is also insulation provided between the windings [5]. Probably the most popular are the planar EE and EPLT cores, which are designed specifically for planar magnetics and currently offered by most manufacturers in many industry standard sizes. Cores for planar components, as shown in Figure 4.

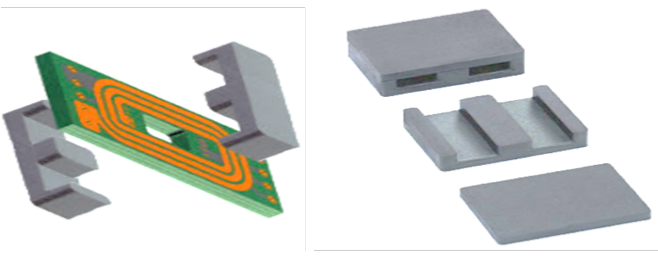

Fig 4. Typical planar core shapes.

Most of the transformer planar core materials are made of soft ferrites due to their reduced core loss. Core material are 3C80, 3C92, 3C94, 3C97, 3F3 and so on. Based on the dimension of these core materials design of PCB windings [10,11].

3.2. Flyback Converter

Continuous conduction mode (CCM) and discontinuous conduction mode (DCM) have advantages and disadvantages, respectively [12, 13]. In general, DCM provides better switching conditions for the rectifier diodes, as the diodes operate at zero current before becoming reverse biased. Since the average energy storage is small compared to CCM, the size of the flyback transformer can be reduced by using DCM. However, DCM causes high RMS current. Meanwhile, CCM means that all the energy stored in the inductor is not used in each cycle, so a larger transformer size is needed for the higher total energy. Since the current never drops to zero (being continuous), the ripple in the input and output current of a flyback converter which is shown in Fig.5 is lower.

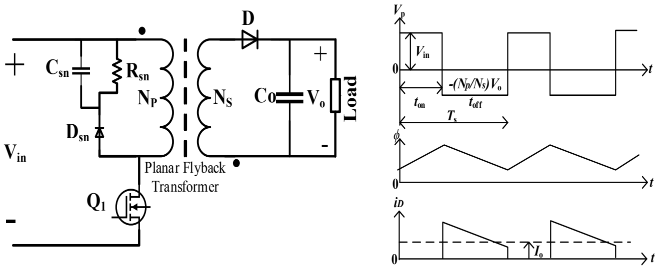

Fig 5. Flyback converter and related waveforms.

The transformer of the flyback converter temporarily stores energy when the switch is open. In this time period, the capacitor at the output feeds the load. When the switch is closed, the energy stored by the flyback transformer is transferred to the load through the output diode. When the switch of the flyback converter is off, there is a high voltage spike inductance on the drain due to the transformer leakage [14]. The most common snubber used is a snubber with a resistor, capacitor and diode also known as RCD snubber shown in Fig. 5.

3.3. Design of Flyback Planar Transformer

The planar flyback transformer was designed for V_{inmin} which is battery set voltage of 24 VDC. The output voltage of the driver, Vo is 12 V. For the optimal design and transferring the stored energy of the flyback converter, the maximum duty cycle (D_{max}) of the switch is set to 0.45 according to the switching frequency (f_s) which is constant (50 kHz) and the output power (P_o) of 50 W. In order to design the flyback planar transformer, determination of the following parameters is necessary. L_{pri} (primary inductance), N_p (primary winding turn number), N_s (secondary winding turn number), I_{ppeak} (peak value of primary current). and I_{speak} (peak value of secondary current). The related equations necessary for planar flyback transformer are given below [12,13, 15, 16].

$$N_p = \frac{Vin_{min} . D_{max}}{f_s . B_{peak} . Ae} \tag{1}$$

$$n = \frac{Vin_{min}}{V_O} . \frac{D_{max}}{(1 - D_{max})} \tag{2}$$

$$Ns = \frac{Np}{n} \tag{3}$$

$$I_{av} = \frac{P_o}{\eta . Vin_{min}} \tag{4}$$

$$I_{ppeak} = \frac{I_{av}}{D_{max} . (1 - 0.5 * K_{RP})} = \frac{I_{av}}{0.5 . D_{max}} \tag{5}$$

$$L_{pri} = \frac{2 . P_{in}}{f . I_{ppeak}^2} \tag{6}$$

$$G = \frac{Np^2 . \mu_o * Ae}{L_{pri}} \tag{7}$$

$$I_{prms} = \sqrt{D_{max} . \frac{I_r^2}{3}} \tag{8}$$

$$I_{speak} = I_{ppeak} . n \tag{9}$$

$$I_{srms} = I_{speak} . \sqrt{\frac{D_S}{3}} \tag{10}$$

$$I_{sav} = \frac{P_O}{V_O} \tag{11}$$

where; B_{peak} (peak flux density), A_e (Effective Cross-sectional area), n (Turn Ratio), I_{av} (Primary Average Current), μ_o (Permeability of Free Space). KRP (Ripple to Peak Current Ratio), P_{in} (Input Power), G (Airgap Length), I_{prms} (Primary rms Current), I_{srms} (Secondary Output Current), D_s (Secondary Duty Cycle), I_{sav} (Secondary Average Current) and η (Efficiency of Transformer)

As stated before, when the switch of the flyback converter turned off, there is a high voltage spike inductance on the drain due to the transformer leakage. The MMF is distributed more evenly by interleaving the windings with each other, which results in a higher physical coupling between the primary and secondary winding.

$$V_{RO} = \frac{D_{max}}{(1- D_{max})} . Vin_{min} \quad (12)$$

(n*vo = VRO is the reflected output voltage on the primary side. The power dissipated by the snubber circuit can be written as:

$$P_{sn} = \frac{(V_{sn})^2}{R_{sn}} = \frac{1}{2} . f_s . L_{lk} . (I_{ppeak})^2 . \frac{V_{sn}}{(V_{sn}- V_{RO})} \quad (13)$$

Snubber capacitor voltage V_{sn} should be larger than VRO and it is typical to set V_{sn} to be 2~2.5 times of VRO. The snubber resistor needed to dissipate this amount of power which can be calculated with Equation 14.

$$P_{sn} = \frac{(V_{sn})^2}{R_{sn}} \quad (14)$$

The capacitor needed for the snubber can be calculated with the Equation 15.

$$C_{sn} = \frac{V_{sn}}{(\Delta V_{sn} . R_{sn} . f_s)} \quad (15)$$

4. Results and Discussion

The proposed PV powered flyback planar transformer-based LED illumination driver which is shown in Fig. 6 was designed and simulated in MATLAB/Simulink. It can be seen from the figure, the proposed system contains two subsystem, solar battery charge subsystem and LED driver subsystem. The first stage (solar battery charge subsystem) of the proposed driver which is studied in [17-18] converts the solar energy and charges the battery set with MPPT. The second stage (planar flyback-based LED driver subsystem) of the system is fed from the battery set and converts the energy to LED load via planar flyback transformer.

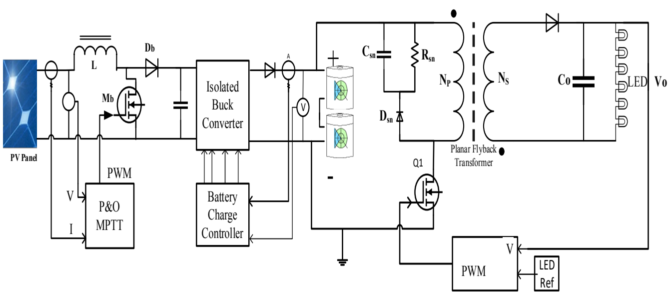

Fig 6. Proposed Battery Charge subsystem.

The main specifications of the proposed PV powered flyback planar transformer-based LED illumination driver which is simulated in MATLAB/Simulink are given in Table 1, while the general specification of selected cores is given in Table 2. According to equations 1-11, the planar flyback transformer was designed for nominal 50 W power and 24 V battery as source and 12 V Output voltage. PLT38/25/3.8 core was selected for designing the planar transformer.

Table 1. Specifications of the proposed system

Parameter	Value
PV Nominal Powe	250 Wp
Battery Set Voltage	24 V
Battery Nominal Capacity	45 Ah
LED Nominal Power	50 W
Output Voltage (Vo)	12 V
Switching frequency (fs)	50 KHZ
Snuber resistance	940 Ω /2.5W
Snuber capacitor	220 nF/ 63 V

Table 2. General specification of selected convectional and planar EE Core

Type / Parameter	Planar transformer	Conventional transformer
Core Weight (gr)	18	58
Core Dimension (mm)	38.1*25.4*12.07	40.6*12.5*33
Core Height (mm)	12.07	33
Core Area(mm2)	967.74	507.5
Core volume (cm3)	5.926	26.3667
Winding volume (cm3)	5.399	24
Losses (W)	1.896	1.946

The planar flyback transformer was designed according to related equations given former section and the obtained results are given in Table 3.

Table 3. Design parameters of the planar flyback transformer

B_{peak} (T)	P_{core} (W)	N_p	N_s	I_{av} (A)	I_{ppeak} (A)	L_{pri}(μH)
0.22	0.766	12	8	2,126	9,448	22,86
$P_{cop.}$ (W)	Prim. Patch	Pat. Thi (μm)		Pri. No in Lay.	Pri. No in Lay.	L_{sec}(μH)
3.833	1400 μm	0.7665		3	2	8.542

The P&O method, whose flow diagram is given in Fig.7 [8,9] was used for the solar battery charge subsystem of the proposed LED driver.

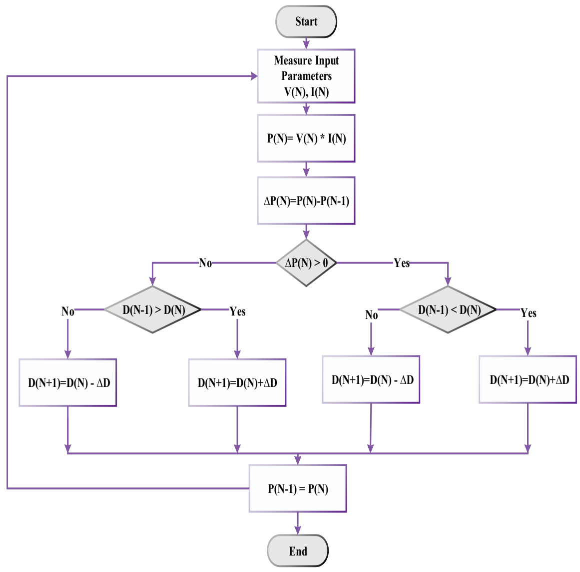

Fig 7. P&O method flowchart.

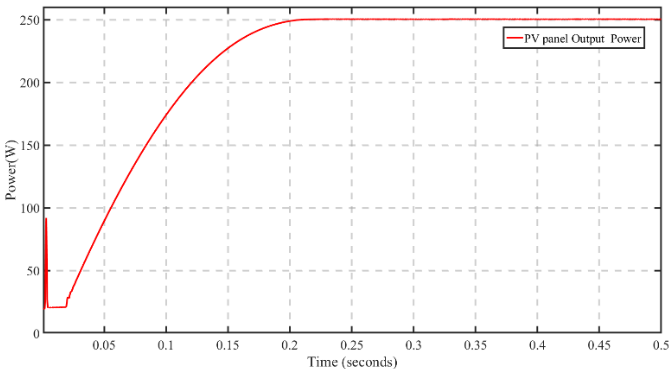

Fig 8. PV panel output power under standard test condition.

While the output power of PV panel used in this system is given in Fig. 8. The battery bus and boost output voltages of battery charging subsystem is shown in Fig.9. It is seen that the maximum power can be obtained from the PV panel via P&O MPPT method. The Boost DC/DC converter voltage was dropped to acceptable battery charging level by using a H-bridge based insulated DC/DC buck converter.

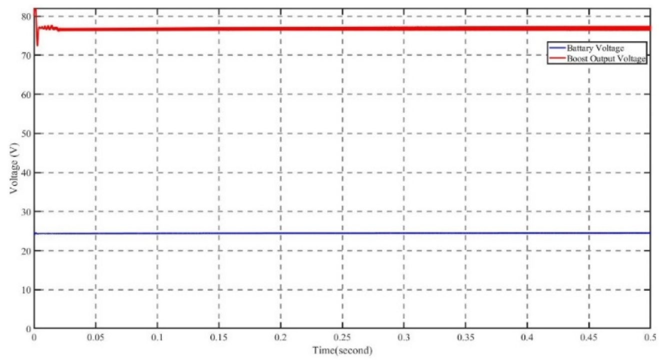

Fig 9. Boost output voltage and battery voltage of battery charging subsystem.

The battery charging current and charge percentage is given in Fig. 10. The output voltage of flyback LED driver subsystem is given in Fig. 11. The commercial LED required for a 12 V. The subsystem has a 12 V output voltage with less than 1% of ripple.

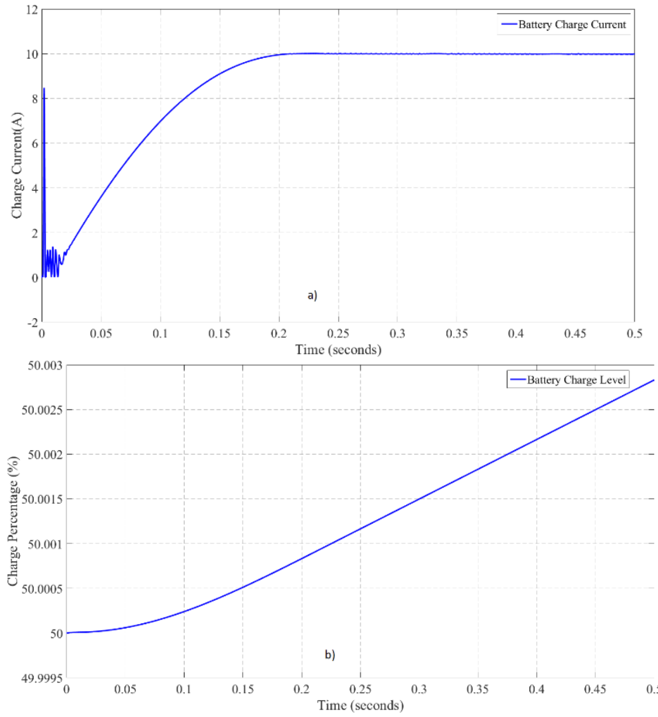

Fig 10. Battery charging a) current and b) percentage.

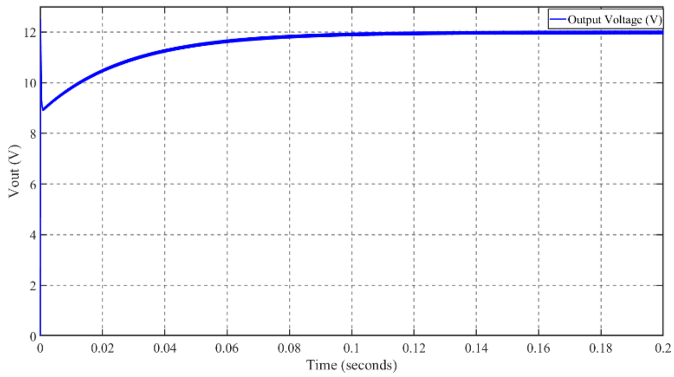

Fig 11. The output voltage of flyback LED driver.

The flyback transformer was designed in DCM mode and Fig. 12 shows the PWM signal of driver that produced by using a PI controller. In addition, while the primary and secondary windings currents are given in Fig. 12, the primary and secondary windings voltages are given in Fig. 13.

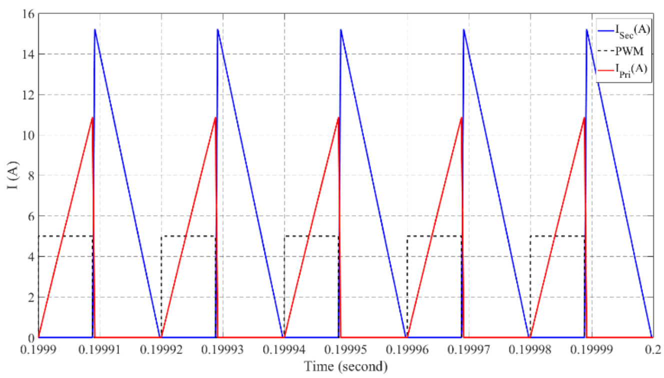

Fig 12. Input current, output current and PWM signal of the planar flyback converter.

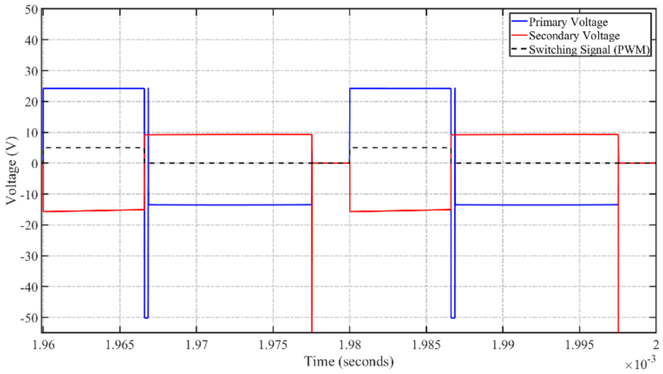

Fig 13. Primary and secondary voltages of the planar flyback converter

5. Conclusion

This paper presents a designing of planar flyback transformer for solar LED illumination system. The proposed system contains two subsystem, solar battery charge subsystem and flyback based LED driver subsystem. A detailed design methodology for flyback planar transformer with details on the printed circuit board (PCB) layer is presented and simulation for planar flyback converter are performed. The transformer is an essential element of any power supply design. Planar transformers have been shown to be more suitable for soft-switched power supply designs over conventional wire-wound transformers (classical models), because the planar magnetics provides greater efficiency, high performance in power density, super repeatability, excellent heat dissipation, smaller in size and lighter in weight at about half the weight of a conventional magnet. Planer transformers provide more options for modifying and utilizing parasitic parameters than conventional models. PCB planar transformers have been shown to be mostly used to miniaturize power converters, and with thinner conductors. Planar PCB transformers are also used to reduce high frequency effects.

The essential equations for designing of flyback PT are introduced and evaluated. The designed flyback PT was used in 50W LED illumination driver powered by PV panel with a battery. In the proposed driver which was simulated by using MATLAB/Simulink program, the battery is charged via PV powered boost topology with P&O MPPT method and an insulated H-bridge DC/DC converter. Results of the simulation are closely identical and compatible with the design calculation results. Using the improved PT structure has been designed. A 94% planar transformer efficiency was achieved. Simulation results show that planar flyback converter is worked properly and is a good candidate for high-frequency low power applications. The designing verified by using simulation activities. All simulation results show that planar transformer have better performance and could use as solar based led driver. The dimension and weight of planar transformer is less than convectional EE type flyback transformer. The overall dimensions of system will reduce by using planar transformer. The copper and core losses of planar flyback transformer is less than convectional flyback transformer. This increases the efficiency and reduce the temperature rise of transformer and circuit. Also, its cooling request is less than convectional type.

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