Single Stage Forward-Flyback Converter for Improvement in Performance

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Abstract:
In this paper, combining forward and flyback topology converter together by using suitable switching device (i.e. MOSFET) is proposed to obtain better a performance in terms efficiency and power factor of single stage forward-fly back converter. Fly back converter has several advantages over forward converter that they have better power factor but due to higher offset current through magnetizing inductor. Its core loss increases tremendously which results in poor conversion efficiency. On the hand forward converter can obtain high conversion efficiency with low core loss. But input current dead zone near cross AC input voltage decreases power factor. Considering all above aspects proposed converter operates as proposed forward converter for switching on period and as fly back converter for off period. It transfer power over whole switching and achieve better power factor due to fly back converter. Since conventional system having problem regarding offset current. Then this can be reduced by using balanced capacitor. This minimised core loss and volume of transformer. Therefore proposed converter features high efficiency and power factor. To confirm validity of proposed converter, theoretical analysis with control strategy and experimental results are presented.

Keywords: Forward-Fly back, MOSFET, PFC, THD

I. INTRODUCTION
In recent times, for displays and illumination applications light-emitting diodes (LEDs) used on large extent. It just because of LEDs features such as a better efficiency, long life time and echo-friendliness. Therefore, now a day’s conventional lighting devices such as a light bulb and fluorescent lamp tend to be replaced by LEDs [1, 2]. There are two types of LED drivers are generally used, that are a linear and switch-mode regulators [3]. Among which the linear driver have advantage of a simple circuit configuration, fast transient response and accurate current regulation, but has serious problem such as a low efficiency and more heat generation. As a result, the switch-mode driver is commonly used in LED applications due to its high efficiency and power density [4, 5]. The drivers for LED lightings have been consist of two power conversion stages (i.e. a power factor corrector and isolated DC/DC converter) [6]. The first stage provides a near unity power factor and low total harmonic distortion (THD) over an whole range of universal input voltage (90-270 Vrms) and the second DC/DC stage is used to provide a tight output regulation and galvanic isolation between AC input and DC output. Despite the fact that the two-stage configuration be able to provide the high power factor, good output regulation and excellent ripple voltage, it has a number of major disadvantages such as a large system size, high cost of production and low energy conversion efficiency [8]. For this reason, it is common that the two-stage driver is mostly used for high power applications and single-stage driver is used as a low power LED driver. A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which flows in only one direction. The process is known as rectification. Physically, rectifiers take a number of forms, including vacuum tube diodes, mercury-arc valves, copper and selenium oxide rectifiers, semiconductor diodes, silicon-controlled rectifiers and other silicon-based semiconductor switches. Historically, even synchronous electromechanical switches and motors have been used. Rectifiers have many uses, but are often found serving as components of DC power supplies and high-voltage direct current power transmission systems. Rectification may serve in roles other than to generate direct current for use as a source of power. As noted, detectors of radio signals serve as rectifiers. In gas heating systems flame rectification is used to detect presence of a flame. Because of the alternating nature of the input AC sine wave, the process of rectification alone produces a DC current that, though unidirectional, consists of pulses of current. Many applications of rectifiers, such as power supplies for radio, television and computer equipment, require a steady constant DC current (as would be produced by a battery). In these applications the output of the rectifier is smoothed by an electronic filter (usually a capacitor) to produce a steady current. A more complex circuitry device that performs the opposite function, converting DC to AC, is called an inverter.

II. BASIC CONVERTERS TOPOLOGY
Fly-back converter is the most commonly used SMPS circuit for low output power applications where the output voltage needs to be isolated from the input main supply. The output power of fly-back type SMPS circuits may vary from few watts to less than 100 watts. The overall circuit topology of this converter is considerably simpler than other SMPS
circuits. Input to the circuit is generally unregulated dc voltage obtained by rectifying the utility ac voltage followed by a simple capacitor filter. The circuit can offer single or multiple isolated output voltages and can operate over wide range of input voltage variation. In respect of energy-efficiency, flyback power supplies are inferior to many other SMPS circuits but its simple topology and low cost makes it popular in low output power range. The commonly used fly-back converter requires a single controllable switch like, MOSFET and the usual switching frequency is in the range of 100 kHz. A two-switch topology exists that offers better energy efficiency and less voltage stress across the switches but costs more and the circuit complexity also increases slightly.

Fig.1. Basic Topology of Fly-Back Converter

Fig.1 shows the basic topology of a fly-back circuit. Input to the circuit may be unregulated dc voltage derived from the utility ac supply after rectification and some filtering. The ripple in dc voltage waveform is generally of low frequency and the overall ripple voltage waveform repeats at twice the ac mains frequency. Since the SMPS circuit is operated at much higher frequency (in the range of 100 kHz) the input voltage, in spite of being unregulated, may be considered to have a constant magnitude during any high frequency cycle. A fast switching device (“S”), like a MOSFET, is used with fast dynamic control over switch duty ratio (ratio of ON time to switching time-period) to maintain the desired output voltage. The transformer, in Fig.1, is used for voltage isolation as well as for better matching between input and output voltage and current requirements.

Forward converter is another popular switched mode power supply (SMPS) circuit that is used for producing isolated and controlled dc voltage from the unregulated dc input supply. The forward converter, when compared with the fly-back circuit, is generally more energy efficient and is used for applications requiring little higher power output (in the range of 100 watts to 200 watts). However the circuit topology, especially the output filtering circuit is not as simple as in the fly-back converter Fig.2 shows the basic topology of the forward converter. It consists of a fast switching device ‘S’ along with its control circuitry, a transformer with its primary winding connected in series with switch ‘S’ to the input supply and a rectification and filtering circuit for the transformer secondary winding. The load is connected across the rectified output of the transformer-secondary.

Fig.2. Basic forward converter topology

The transformer used in the forward converter is to be an ideal transformer with no leakage fluxes, zero magnetizing current and no losses. The basic operation of the circuit is explained with different mode operation here assuming ideal circuit elements. In fact, due to the presence of finite magnetizing current in a practical transformer, tertiary winding needs to be introduced in the transformer and the circuit topology changes slightly.

III. CONVENTIONAL CONVERTERS

Fig.3 shows conventional single-stage PFC (power factor correction) LED drivers, which are well known as most cost effective solutions.

(a) Single-stage flyback converter

(b) Single stage forward converter

Fig.3. Conventional single stage PFC converter circuits
Fig. 4. Transformer magnetizing inductor currents of conventional flyback and forward converters

Fig. 4 shows their transformer magnetizing inductor currents. As shown in this figure, the magnetizing inductor offset current of flyback converter is larger than that of forward converter. The magnetizing inductor offset current of flyback and forward converter is

\[ I_{LM, \text{flyback}} = \frac{I_o}{n(1-D)} \]  

\[ I_{LM, \text{forward}} = \left(1 + \frac{N_c}{N_p}\right) \frac{V_{in}}{2L_M} D^2 T_s \]

Moreover, from equations (1) and (2), while the magnetizing inductor offset current of flyback converter is dependent on the load current \( I_o \), that of forward converter is not. Therefore, as the load current is more increased, the offset current of flyback converter becomes larger, which might result in the larger core loss and volume of transformer. For these reasons, the forward converter is superior to the flyback converter in terms of the transformer size and energy conversion efficiency.

IV. PROPOSED CONVERTER

The fig. 5 shows the circuit diagram of the proposed forward flyback converter. Which merges both forward and flyback topology together.

A. Construction and working principle

As shown in fig5, proposed system primary side is exactly same as that of the conventional flyback converter consisting of one power switch (M1) and one transformer. On the other hand, its secondary side consists of one output inductor (Lo) for forward operation, one DC blocking capacitor (Cb) for balancing operation and three output Diodes (D1, D2, D3). When M1 is conducting, the proposed converter operates as a forward converter as shown in Fig 7. On the other hand, when M1 is blocked, the proposed converter operates as a flyback converter as shown in Fig 8. However, if it is assumed that the proposed converter has no balancing capacitor Cb, abovementioned forward operation is possible only when the reflected primary voltage \( V_{in/n} \) to the transformer secondary side is higher than the output voltage \( V_o \). This is because the forward converter is originated from the buck converter.

Therefore, the forward-flyback converter operates only as a flyback converter over the range of \( V_{in/n} < V_o \). Especially, at the minimum input voltage near \( V_{in}=90\text{rms} \), \( V_{in/n} \) is lower than \( V_o \) during most of periods and thus, the transformer has a large magnetizing offset current similar to the conventional flyback converter. In this case, the transformer core loss and volume are also as large as those of the conventional flyback converter. On the other hand, if the balancing capacitor Cb is serially inserted with the transformer secondary side, it can make the average current through Cb during forward operation become exactly same as that during flyback operation by the charge balance principle of Cb. In other words, since the voltage across Cb charged by flyback operation is added to the \( V_{sec}=V_{in/n} \) during forward operation, \( V_{in/n}+V_{cb} \) becomes higher than \( V_o \) and thus, the forward operation is possible even at \( V_{in/n}<V_o \). Therefore, the proposed forward-flyback converter with the balancing capacitor Cb can always operate as both forward and flyback converters regardless of the input voltage. Fig. 6 shows the primary and magnetizing current waveforms of the proposed converter operating in the boundary conduction mode (BCM).

Fig. 6 Primary and magnetizing currents of forward-flyback converter according to the input voltage. (a) without balancing capacitor (b) with balancing capacitor

Fig. 6 (a) and (b) show current waveforms without and with balancing capacitor Cb according to the input voltage, respectively. As mentioned earlier, the proposed converter with Cb can operate as both forward and flyback converters over an entire range of input voltage with the aid of Vcb. On the other hand, while the proposed converter without Cb can transfer the input energy to the output side at \( V_{in/n}>V_o \), it cannot at \( V_{in/n}<V_o \). As a result, the proposed converter with balancing capacitor Cb features a smaller magnetizing offset.
current, resultant smaller core loss and more reduced transformer volume.

B. Mode operation

The operation of the proposed converter is divided into two modes according to the conduction state of each switch

Mode 1 [t₀ − t₁]: When iLM reaches zero, mode 1 begins at t₀. Since M₁ is turned on, Vin is applied to LM and ILM is linearly increased with the slope of Vin/LM. At this moment, although Vsec = Vin/n across the transformer secondary side may be lower than Vo, the sum of Vsec = Vin/n and Vcb applied to the input side of output LC filter is higher than the output voltage Vo. Therefore, as shown in Fig. 7, D₁ is conducting and the input energy is transferred to the load side through forward operation. And, the voltage across D₂ is Vin/n+Vcb and that across D₃ can be clamped on Vo by D₁.

Mode 2 [t₁ − t₂]: When M₁ is turned off at t₁, mode 2 begins. While the energy stored in LM is released to the load side through D₂ and D₃, the transformer secondary current also charges the balancing capacitor Cb as much as discharged quantity in Mode 1. At the same time, the current though Lo freewheels via D₂. Since n(Vo+Vcb) is applied to LM, ILM is linearly decreased with the slope of n(Vo+Vcb)/LM. Subsequently, when ILM reaches zero, M₁ is turned on and the operation from Mode 1 to Mode 2 is repeated.

V. SIMULATION AND RESULT DISCUSSION

Simulation proposed system can be tested with pulse generator or by Proportional & Integral Controllers. Proportional + Integral (PI) controllers were developed because of the desirable property that systems with open loop transfer functions of type 1 or above have zero steady state error with respect to a step input.

The PI regulator is:

\[ C(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} \]

Tuning PI Controllers

General approach to tuning:

1. Initially have no integral gain (TI large)
2. Increase KP until get satisfactory response
3. Start to add in integral (decreasing TI) until the steady state error is removed in satisfactory time (may need to reduce KP if the combination becomes oscillatory)

Fig. 7. Schematic diagram of Simulation Model

The fig. 7 shows systematic model of proposed system. By providing direct gate pulse to MOSFET by using pulse generator or by using PI controller technique both having similar results.

Fig. 8 shows the experimental waveforms of transformer primary current and switch voltage at V_in = 90 and 264 Vrms. As can be seen in this figure, the measured waveform of I_in (=I_p) has a near sinusoidal waveform.

(a) I_p and V_DS measured at Vin = 90 Vrms

(b) I_p and V_DS measured at Vin = 264 Vrms

Fig. 8 Experimental waveforms of transformer primary current and switch voltage.

(a) I_L0 and I_D3

(b) Detail waveforms of I_L0 and I_D3 at low input voltage

Fig. 9. Experimental key waveforms of proposed circuit measured at 90 Vrms.
Fig. 9 shows the experimental waveforms of output inductor current $I_{L0}$ and output diode current $I_{D3}$ at 90Vrms, where $I_{L0}$ corresponds to the forward operating current and $I_{D3}$ flyback operating current. As can be seen $I_{L0}$ and $I_{D3}$ continuously flow even at the low input voltage. Details of waveforms of $I_{L0}$ and $I_{D3}$ at low input voltage can be observed in fig 9 (b). It also observed that same waveforms are obtained. When proposed system implemented with pulse generator and proportional integral controller at low input voltage.

![Waveform Image](image1)

(a) $I_p$ and $V_{DS}$ measured at Vin = 264 Vrms

(b) Detailed waveforms of $I_{L0}$ and $I_{D3}$ at low input voltage

Fig. 10 Experimental key waveforms of proposed circuit measured at 264Vrms.

![Waveform Image](image2)

Fig. 10 shows the experimental waveforms of output inductor current $I_{L0}$ and output diode current $I_{D3}$ at 264Vrms it again found to be same with both control strategies, where $I_{L0}$ corresponds to the forward operating current and $I_{D3}$ flyback operating current. As can be seen $I_{L0}$ and $I_{D3}$ Continuously flow even at the high and low input voltage, which proves that the proposed forward-flyback converter can always operate as both forward and flyback converters regardless of the input voltage.

![Waveform Image](image3)

(a) Magnetizing current waveform without balancing capacitor

![Waveform Image](image4)

(b) Magnetizing current waveform with balancing capacitor

Fig. 11 Simulation waveforms for Magnetizing current using pulse generator control at 90 Vrms.

Fig. 11 shows magnetizing current of proposed forward flyback converter when tested using pulse generator control at 90 Vrms. When proposed converter simulated without balanced capacitor as shown in fig. 11 (a) maximum value of magnetizing current observed to be nearer to 3A at 90Vms.

whereas fig. 11 (b) shows waveform of magnetizing current with balancing capacitor at same voltage. Its maximum value is reduced to 1.1A. Therefore this shows that proposed converter has less magnetizing current and core loss with balanced capacitor than without balanced capacitor.

![Waveform Image](image5)

(a) Magnetizing current without balancing capacitor

![Waveform Image](image6)

(b) Magnetizing current with balancing capacitor

Fig. 12 Simulation waveforms for Magnetizing current using proportional integral control at 90 Vrms.

Fig. 12 shows magnetizing current of proposed forward flyback converter when tested using proportional integral control at 90 Vrms. When proposed converter simulated without balanced capacitor as shown in fig. 12 (a) maximum value of magnetizing current observed to approximately 0.8 A at 90 Vms. Whereas fig. 12 (b) shows waveform of magnetizing current with balancing capacitor at same voltage. Its maximum value is reduced to 0.35 A.

Thus by observing fig. 11 and fig. 12, the magnetizing offset current of the proposed converter is lower than that of the fly back converter with the aid of the balancing capacitor $C_b$. This can be again reduced when proposed system operated with proportional integral. As a result, the proposed converter can achieve the smaller transformer core loss and higher efficiency.

**VII CONCLUSION**

A single stage high performance balanced forward-flyback converter for LED application is presented, and its operation principle analyzed in this paper. The proposed forward-flyback converter tested with and without balanced capacitor. It is observed that the with balancing capacitor proposed converter can always operate as both forward and flyback converters regardless of the input voltage. Therefore, it has a smaller magnetizing offset current, resultant smaller core loss and more reduced transformer core volume. For this reason, the proposed converter can be obtained high efficiency and performance. To verify the validity of proposed circuit, experimental results from a prototype of 24W single stage balanced forward-flyback converter for LED application are provided. Proposed converter can be operated with pulse generator control and PI control. Both system having similar result waveforms for primary current versus switch voltage, Output inductor current versus output diode current. But for magnetizing current using pulse generator control at 90Vms without balance capacitor maximum value observed to
be 3A. When balanced capacitor inserted its value becomes 1.1A. This value can be again reduced to 0.35A by using proportional integral. Thus system capable to achieves minimum magnetizing current and core loss.

Moreover, the proposed circuit can perform the power transfer during an entire switching period with minimum value of magnetizing current using proportional integral than pulse generator. Therefore, the proposed circuit having these favorable advantages is expected to be well suited to various LED driver applications.

REFERENCES


