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Closed Loop Controlled High Efficiency Forward Flyback Converter

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Abstract:

This paper presents the single-stage high efficiency Forward-Flyback converter with high power factor. Flyback converter uses few components and a simple control method to increase input power factor. Single-Stage ac/dc converters have received much attention in the past decades because of its cost effectiveness, compact size, and simple control mechanism. Among existing Single-Stage converters, most of them are comprised of a boost power-factor correction (PFC) cell followed by a dc/dc cell for output voltage regulation. The conventional forward converter can achieve the good power conversion efficiency with the aid of the low core loss but the input current dead zone near zero cross AC input voltage deteriorates the power factor. On the other hand, since the proposed converter can operate as the forward and fly back converters during switch on and off periods, respectively, it cannot only perform the power transfer during an entire switching period but also achieve the high power factor due to the flyback operation.The proposed concept is implemented with closed loop operation by using MATLAB/SIMULATION software. The closed loop operation provides automatic control over the output and reduction of the switching losses.

Index terms:
Forward-Flyback converter, ac/dc converters.

I.INTRODUCTION:

Recently, light-emitting diodes (LEDs) are becoming increasingly attractive lighting sources in our daily livesbecause LEDs have several favorable advantages such as a high efficiency, long life time and echo-friendliness. They are well suited to indoor and outdoor energy-saving lighting applications, such as general lighting, architectural lighting, traffic lighting, background lighting, displays, street lighting, automotive and motorcycle lighting, decorative lighting, and so on.

Therefore, traditional lighting devices such as a light bulb and fluorescent lamp tend to be replaced by LEDs [1, 2]. To drive LEDs, two types of drivers are generally used, that are a linear and switch-mode regulators [3].Although the linear drivers such as controlled rectifiers have a simple circuit configuration, fast transient response and accurate current regulation, they havefatal drawbacks such as a low efficiency and serious heat generation. Therefore, the switch-mode driver is widely used to feed LEDs due toits high efficiency and high power density [4, 5].The power drivers for LED lightings havecomposed of two power conversion stages viz. a power factor corrector and isolated DC/DC converter respectively [6]. The power factor corrector stage provides a near unity power factor and low total harmonic distortion (THD) over an entire range of universal inputvoltage (90-270 Vrms) and the second DC/DC stageprovides a tight output regulation and galvanic isolation between AC input and DC output. Even though the two-stage configuration can provide the high power factor, good output regulation and excellent ripple voltage, it has several significant disadvantages such a`s a large system size, high cost of production and low energy conversion efficiency [8]. Therefore, it is common that the two-stage driver is mainly used for high power applications and single-stage driver is adopted as a low power LED driver [9, 10].

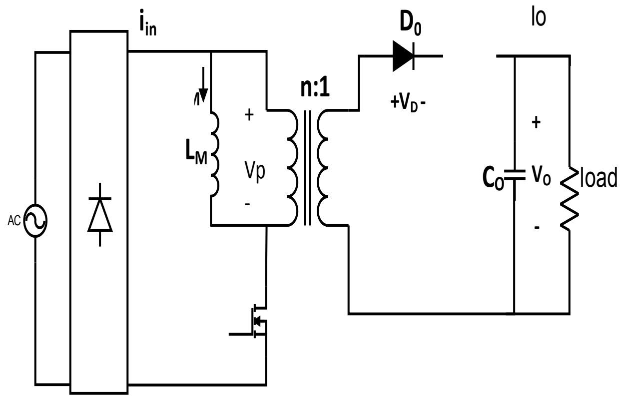

Fig 1 Conventional flyback converter

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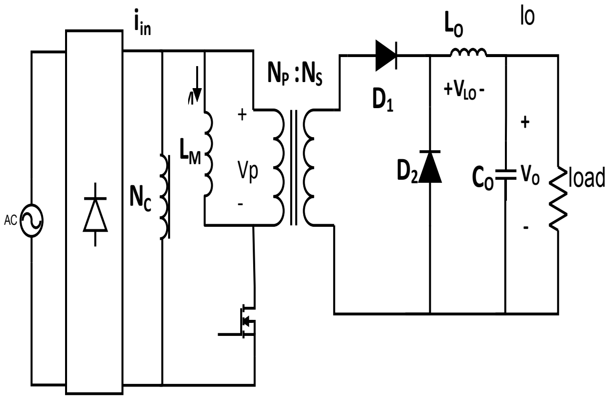


Fig 2:Conventional forward converter

Generally there are two types of switch mode power supplies.Flyback converter and forward converters are most widely used which provide the most cost effective solutions. Fig.1 shows conventional single-stage flyback converter and Fig.2 shows the single stage forward converter. Fig. 3 shows their transformer magnetizing inductor currents. As shown from theFig. 3, the magnetizing inductor current of flyback converter is larger than that of forward converter.

$$I_{LM,Flyback}=\frac{I_o}{n(1-D)} \quad (1)$$

$$I_{LM,Forward}=(1+\frac{N_C}{N_P})\frac{V_{IN}}{2L_M}D^2T_S \quad (2)$$

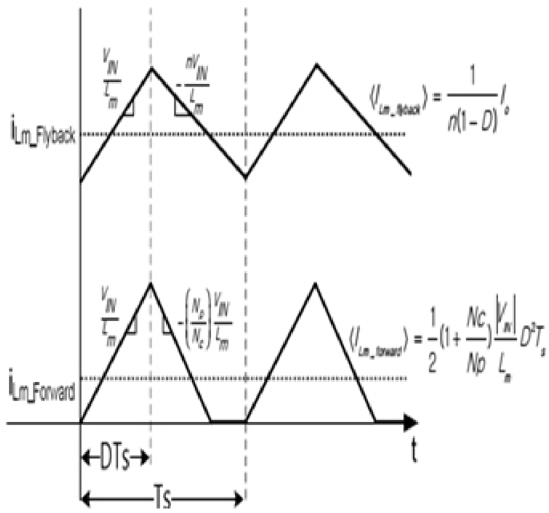
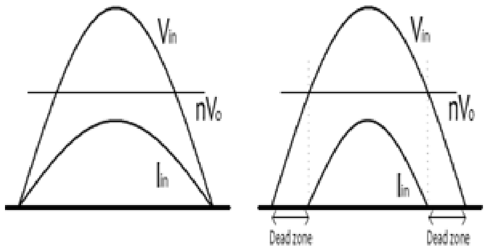


Fig.3. Magnetizing inductor currents comparison of conventional converters

The equations (1) and (2) gives the expression for magnetizing inductor currents for flyback converter and forward converters. The magnetizing current of flyback converter is dependent on the load current i0 whereas the forward converter is doesn't depend on the load current. As the load current increases the magnetizing current of flyback converter increases which results in increased size and core loss in the transformer. As the magnetizing loss in the forward converter is less it has reduced size and high conversion efficiency.



(a)Flyback converter (b) Forward converter
Fig 4. Converter current conduction

Fig. 3,shows the current conduction for forward and flyback converters while the flyback converter can transfer the input energy to the output side over an entire range of input voltage, the forward converter cannot conduct at the lower input voltage than the reflected output voltage nV0on the primary side of the transformer. This is because the forward converter is originated from the stepdown buck topology. Therefore, it leads to a dead zone in the forward converter.

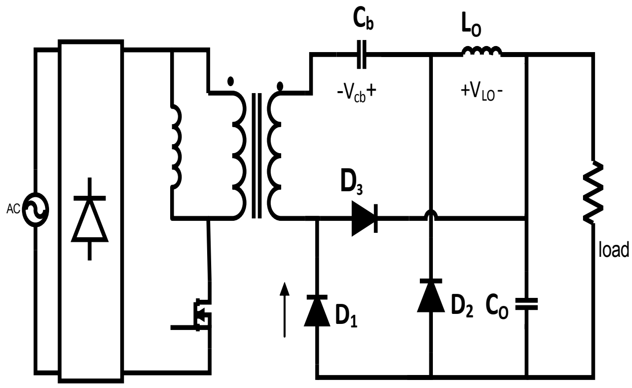


Fig. 5. Circuit diagram of the proposed converter

The input current dead zone near zero cross of AC input voltage is always observed and it deteriorates the input power factor in the forward converter. Therefore, the flyback converter is superior to the forward converter in terms of the power factor performance. To overcome these problems a high efficiency and high power factor single-stage balanced forward-flyback converter is proposed as shown in Fig. 5.

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The proposed converter merges both the forward and flyback converter topologies. This converter operates as the forward converter during switch turn-on and as flyback converters during turn off periods. Therefore the converter performs the power transfer during an entire switching period and also achieves the high power factor. The charge balancing capacitor Cb makes the proposed forward flyback converter perform the forward operation regardless of the input voltage, the magnetizing inductor offset current, core loss and transformer size can be minimized.

II.OPERATINGPRINCIPLE
A. Circuit Operation:

The circuit diagram of the proposed forward flyback converter is shown in Fig 6. The primary side of the transformer is exactly same as that of the conventional flyback converter which consists of a power switch (M1) and one transformer.

Whereas the secondary side consists of one output inductor (Lo) for forward operation, one DC blocking capacitor (Cb) which provides 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 8. When M1 is turned off, the proposed converter operates as a flyback converter as shown in Fig.9.

If it is assumed that the proposed forward flyback converter has no balancing capacitor Cb, abovementioned forward operation is possible only when the reflected primary voltage,Vin/n to the transformer secondary side is greater than the output voltage V0 (i.e.Vin/n>V0). This is because the forward converter is originated from the buck topology.

Thus the forwardflyback converter operates only as a flyback converter over the range Vin/n < Vo. Since the proposed converter has wide operating range, at minimum input voltage i.e. near Vin=90Vrms, most of the periods the reflected voltage Vin/n is lower than V0 and thus, the transformer has a large magnetizing 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.

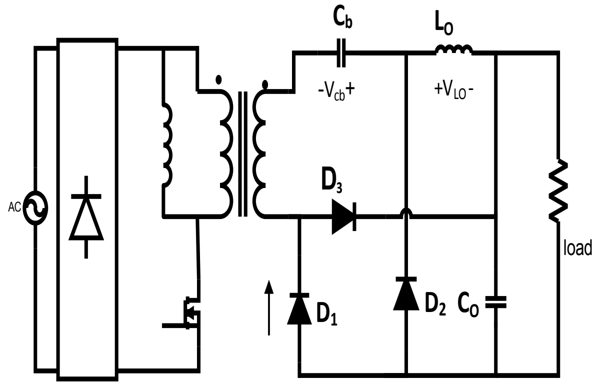

Fig.6. Proposed single stage forward flyback converter circuit

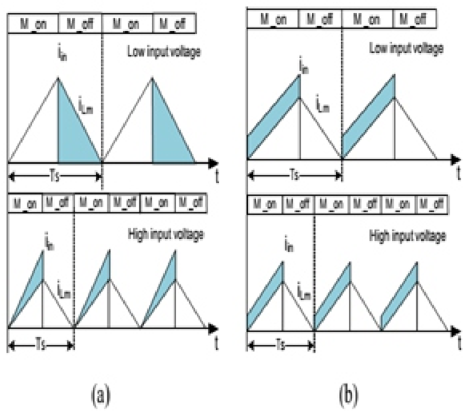

Fig. 7.Magnetizing and Primary currents of forward-flyback converteraccording to the input voltage (a) Without balancing capacitor (b) with balancing capacitor

But, if the balancing capacitor Cb is inserted serially at 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 Vsec=Vin/n during forward operation, Vin/n+Vcb becomes higher than V0 and thus, the forward operation is possible even at Vin/n<V0. 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. 7 shows the primary and magnetizing current waveforms of the proposed converter operating in the boundary conduction mode (BCM). And, Fig. 7 (a) and (b) show current waveforms without and with balancing capacitor Cb according to the input voltage, respectively.

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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 Vin/n>V0, it cannot at Vin/n<V0. 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 analysis.

The operation of the proposed converter is divided into two modes according to the conduction state of each switch as shown in Fig. 8 and 9 and its key waveforms are shown in Fig. 10. For the convenience of the mode analysis in steady state, several assumptions are made as follows:

(a) The switch M1 is ideal except for its internal diode.

(b) The transformer is ideal except for its magnetizing inductance LM.

(c) The output capacitor Co and DC blocking capacitor Cb are large enough to be considered as constant DC voltage sources Vo and Vcb, respectively.

(d) The proposed circuit is operated in boundary conduction mode (BCM).

Before the instant t0, it is assumed that M1 is blocked and the energy stored in LM is being transferred to the load side through D3 and D1. At this moment, Cb is charged by ILM and IL0 is freewheeling through D2.

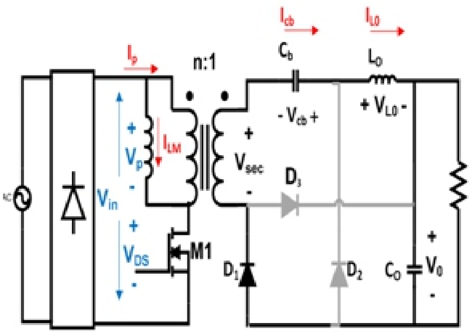

Fig.8. Mode 1 circuit operation

Mode 1[t0~t1]: Mode 1 begins at t0, when iLM reaches zero.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 V0, the sum of Vsec= Vin/n and Vcbis applied to the input side of output LC filter which is higher than the output voltage V0. Therefore, as shown in Fig. 8, D1 is conducting and the input energy is transferred to the load side through forward operation.

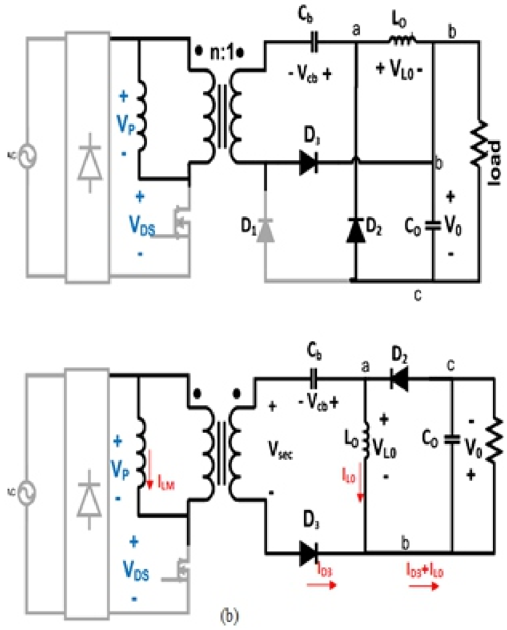

Fig.9. Mode 2 circuit operation(a) circuit operation (b) mode2 equivalent circuit

And, the voltage across D2 is Vin/n+Vcb and that across D3 can be clamped on Vo by D1.

Mode 2[t1~t2]: Mode 2 begins when M1 is turned off at time t1, the balancing capacitor Cbis charged in this mode as much as discharged quantity in Mode 1. At the same time, the current though L0 freewheels via D2. Since n(V0+Vcb) is applied to LM, ILM is linearly decreased with the slope of n(V0+Vcb)/LM.

Subsequently, when ILM reaches zero, M1 is turned on and the operation from Mode 1 to Mode 2 is repeated. While the energy stored in LM is released to the load side through D2 and D3, the transformer secondary current alsocharges the balancing capacitor Cbas much as discharged quantity in Mode 1.

At the same time, the current though Lofreewheels via D2. Since n(Vo+Vcb) is applied to LM, ILMis linearly decreased with the slope of n(Vo+Vcb)/LM. Subsequently, when ILMreaches zero, M1is turned on and the operation from Mode 1 to Mode 2 is repeated.

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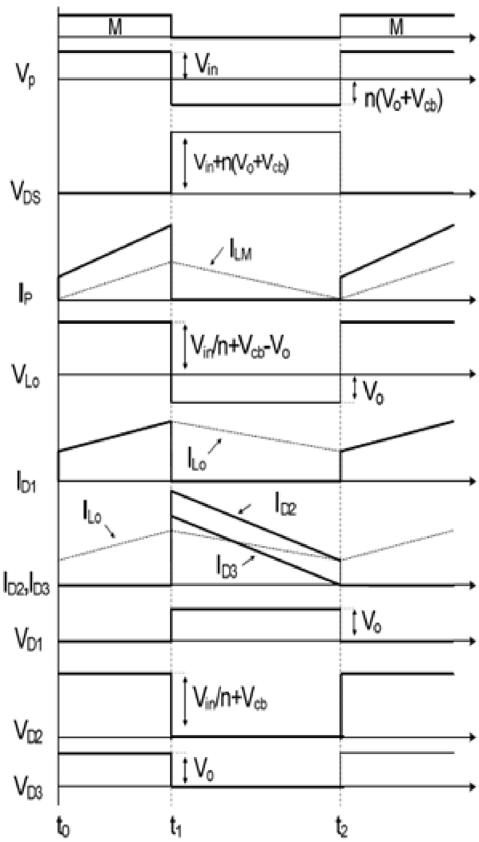

Fig. 10. Key waveforms of the proposed forward-flyback converter

III. ANALYSIS OF THE PROPOSED CONVERTER

A. Voltage conversion ratio:

The voltage conversion ratio of the proposed converter can be obtained by applying the volt-second balance rule on LM and Lo. As can be seen in Fig. 9, the voltage across LM is Vin and n(Vo+Vcb) during t1-t0=DTS and t2-t1=(1-D)TS, respectively. Therefore, following equation can be obtained.

VinD= n(V0+Vcb)(1-D) (3)

Where D and TS are operating duty ratio and one switching cycle, respectively. Similarly, the voltage across Lo is Vin/n+Vcb-Vo and V0 during t1-t0=DTS and t2-t1=(1-D) Ts, respectively. Therefore, following equation can also be obtained.

$$V_0=\frac{DV_{in}}{n}+DV_{cb} \qquad (4)$$

Combining equations (3) and (4) gives the voltage V_{cb} across the balancing capacitor C_b as

$$V_{cb}=DV_0=\frac{D^2}{n(1-D^2)}V_{in} \qquad (5)$$

From equation (3) and (5), the output voltage V_0 can be obtained as

$$V_0=\frac{DV_{in}}{n(1-D^2)} \qquad (6)$$

B. Voltage stresses across the switch and diode:

As mentioned earlier, when M1 is turned off, the voltage VDS across M1 is the sum of input voltage Vin and reflected voltage n(Vo+Vcb) to the transformer primary side. Therefore, the voltage stress of M1 can be represented by

$$V_{DS,stress}=V_{in}+n(V_0+V_{cb}) \quad (7)$$

D1 and D3 among three output diodes are clamped on V_o. Therefore, their voltage stresses are determined by V_o. When the switch M1 is conducting, the voltage stress of D2 is expressed by

$$V_{D2,stress}=\frac{V_{in}}{n}+V_{cb} \qquad (8)$$

Fig. 11 shows comparisons of voltage stresses according to the transformer turn ratio n between conventional flyback and proposed forward-flyback converters. For the convenience of comparative analysis, input and output specifications are assumed as Vin=90~264Vrms and Vo=42V.

As can be seen in this figure, the higher turn ratio can more decrease the diode voltage stress but more increase the switch voltage stress, and vice versa. Especially, the switch voltage stress of the proposed converter is somewhat higher than that of the conventional one due to the balanced capacitor voltage Vcb.

Therefore, in designing the transformer turn ratio, the switch voltage stress must be carefully considered.

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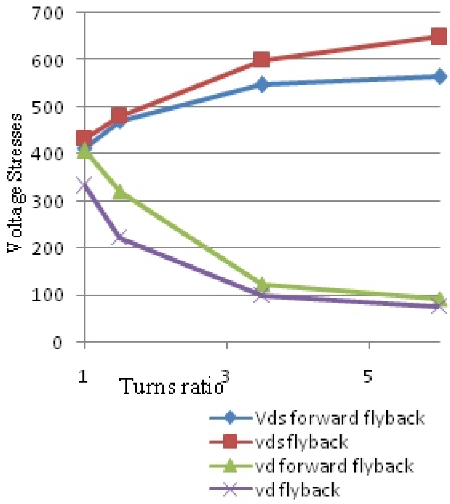

Fig.11. Comparisons of voltage stresses between conventional flyback and proposed forward-flyback converters

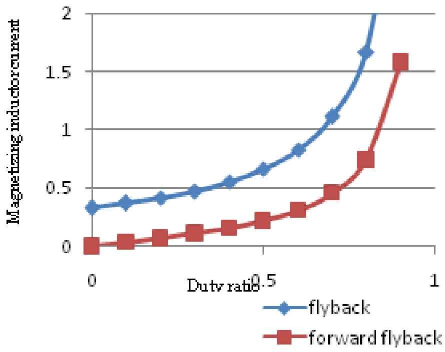

Fig.12. Magnetizing offset currents of conventional flyback and proposed forward-flyback converters according to the operating duty ratio

C.Magnetizing inductor current of transformer:

The offset current of transformer magnetizing inductor generally determines the volume and core loss of the transformer. Therefore, the smaller offset current of LM is the better.

The offset current ILM though transformer magnetizing inductor LM can be calculated by the sum of average primary current Ip and reflected average secondary current Isec/n to the transformer primary side.

Therefore, the conventional flyback converter has following offset current of LM.

$$I_{LM} = \frac{1}{n(1-D)} I_0 \qquad (9)$$

Where Io is the average load current On the other hand, since the average current I_{sec} of transformer secondary side is zero due to the serially connected balancing capacitor Cb, the offset current I_{LM} though L_M is equal to the average primary current I_p. Therefore, the proposed forward flyback converter has following offset current of L_m.

$$I_{LM} = \frac{D}{n(1-D^2)} I_0 \qquad (10)$$

Based on equations (9) and (10), the magnetizing offset currents of conventional flyback and proposed forward-flyback converters according to operating duty ratio are shown in Fig. output specifications are assumed as Vin=90~264Vrms, Vo=42V and Io=0.57A. As shown in this figure, the magnetizing offset current of the proposed converter is lower than that of the flyback converter with the aid of the balancing capacitor Cb. As a result, theproposed converter can achieve the smaller transformer core loss and higher efficiency.11. For the convenience of comparative analysis, input andoutput specifications are assumed as Vin=90~264Vrms, Vo=42V and Io=0.57A. As shown in this figure, the magnetizing offset current of the proposed converter is lower than that of the flyback converter with the aid of the balancing capacitor Cb. As a result, the proposed converter can achieve the smaller transformer core loss and higher efficiency.

IV.SIMULATION RESULTS:

The proposed converter is simulated in MATLAB Simulink and the Fig. 13 shows the simulation block of the open loop simulation and the Fig. 14 shows the output voltage form of the proposed converter for input voltage of Vm=250 V and duty ratio of 50%. The proposed converter is operated in closed loop with PI controller as shown in Fig. 15 the integral controller reduces the error. Apart from this the closed loop operation has various advantages such as high efficiency due to reduced switching losses,automatic control over theoutput, andless sensitive to parameter variations in the converter. Since the proposed converter can operate at wide operating range of input voltages the desired output can be easily obtainable by setting the reference voltage, without any manual adjustment of duty ratio.

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The output voltage of the closed loop operation is shown in Fig. 16 The Fig. 17 shows the power factor comparison of the proposed forward flyback converter and the conventional flyback converter which show the power factor the proposed converter is higher than the conventional converter. The Fig.18 shows the efficiency comparison of the open loop operation of the proposed converter, its closed loop operation and flyback converter. It is observed that the flyback converter has higher efficiency than that of the flyback converter and the with closed loop operation the efficiency is further increased.

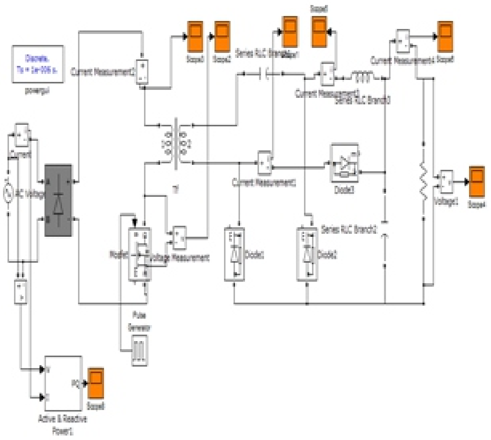

Fig.13Matlab/Simulink model of conventional model

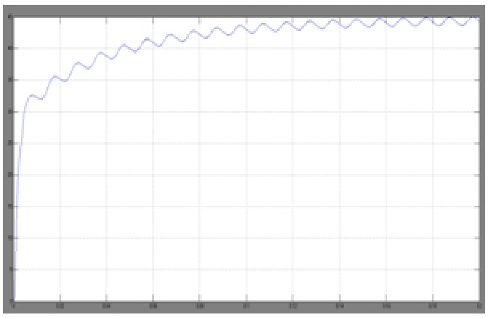

Fig.14Output voltage of the conventional converter

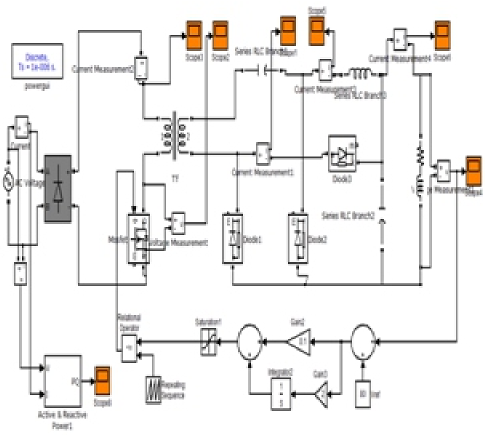

Fig.15Matlab/Simulink model of proposed closed-loop model

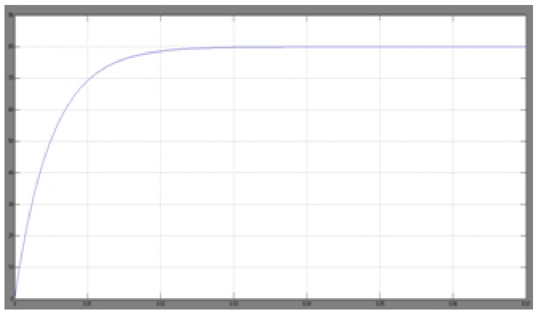

Fig.16The output voltage of the proposed converter

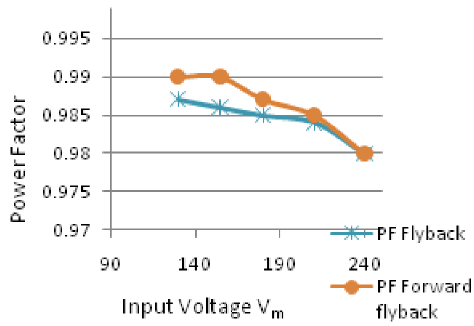

Fig 17 Power Factor Comparison

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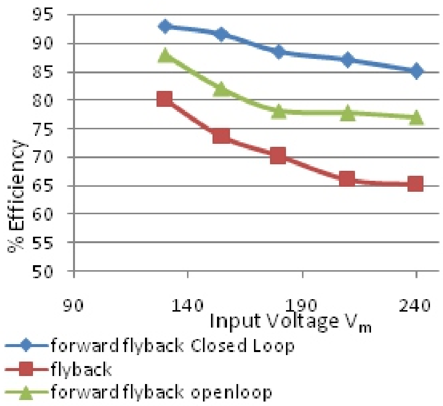

Fig 18 Efficiency comparison

V. CONCLUSION:

A single stage high efficiency balanced forward flyback DC to DC converter is presented, and its operation principle analyzed in this project. The converter obtained has high efficiency of 93% and high power factor of 0.99 and is compared with the flyback converter. The converter obtains variable DC output voltage. The proposed forward-flyback converter with the balancing capacitor 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 obtain high efficiency and high power factor. Moreover, the proposed circuit can perform the power transfer during an entire switching period hence continuous conduction takes place. The proposed circuit, having these favorable advantages is expected to be well suited to various LED driver applications and other DC applications. With implementation of closed loop automatic control is achieved along with reduction of losses and ripples are further reduced.

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