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Research Article

A Boosting Multi Flyback Converter for Electric Vehicle Application

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Abstract: The Flyback converter belongs to the primary switched converter family, which means there is isolation between input and output. Flyback converters have low number of components compared to other Switched Mode Power Supplies (SMPSs), they also have the advantage that several isolated output voltages can be regulated by one control circuit. This study proposes an efficient and cost effective Multi Flyback topology, an isolated DC-DC converter suitable for electric vehicle applications especially driven with induction motor. The converter topology forms a power interface between the battery and the motor and also capable of boosting the voltage from low voltage battery side to high voltage DC link. A Multi Flyback Converter topology implemented by paralleling three individual flyback converters at the battery input side and DC link output side. The topology will share the current across each individual converter and the individual power will be added up at the output side. The scheme incorporates a transformer winding technique which can reduce the leakage inductance of the coupled inductor to a satisfactory limit.

Keywords: Boost converter, fly back converter, isolated DC-DC converter, multi flyback converter

INTRODUCTION

Single-stage AC-DC conversion is a more attractive solution than two-stage conversion from the angle of the cost and power density. In applications like battery chargers, Plasma Display Panel (PDP)-sustaining power supplies and LED lighting; low frequency 100 or 120 Hz, large output voltage ripple is not effective (Bellur and Kazimierczuk, 2008; Hua *et al*., 1994; Wang, 2008; Lin and Hsieh, 2007; Chung *et al*., 1999, 1997; Adib and Farzanehfard, 2008a, b, 2009; Panov and Jovanovic, 2002; Majid and Abbas, 2013; Venkanna *et al*., 2014). Linear regulators are used in ground-based equipments where the generation of heat and low efficiency are not of major concern. PWM switching power supplies are more efficient and flexible than linear regulators. Resonant technology power supplies are the variation on PWM switching power supply finds its place in applications where light weight, smaller size and where a reduced amount of radiated noise is desired (Bellur and Kazimierczuk, 2008; Hua *et al*., 1994; Wang, 2008; Lin and Hsieh, 2007; Chung *et al*., 1999; Sivachidambaranathan and Subhransu, 2010; Mayakkannan and Rajapandian, 2009).

At the maximum voltage the power switches experience, the greater likelihood that they will exceed their Safe Operating Areas (SOA). In switching power supplies, voltage spikes are very common and these spikes exceeding the avalanche voltage rating of the power switch becomes more probable. For transformer isolated topologies, the industry has settled into certain topologies that they use within the different ranges of applications. For below 100 to 150 W, the flyback topology is the ideal choice because of its low parts count, cost and efficiency. Since its peak currents are higher than the forward-mode converters, it reaches the SOA limits of the power switches at a relatively low output power.

Switching converters are divided into two categories: Hard switching and soft switching converters. In hard switching due to overlapping of voltage and switch current during switching instance, the switching loss is high. In soft switching converter, the problems of hard switching can be solved by adding circuit or control procedure and the switching losses, EMI and RFI noises are reduced. The soft switching converters can be divided into three types: Zero Voltage Switching (ZVS), Zero Current Switching (ZCS) and Zero Voltage and Zero Current Switching (ZVZCS). The switching under ZCZVS condition has better function than the other two methods (Bellur and Kazimierczuk, 2008; Hua *et al*., 1994; Lin and Hsieh, 2007; Adib and Farzanehfard, 2008b; Samuel Rajesh Babu and Henry, 2011; Sukhi and Padmanabhan, 2008).

By operating the circuit in the critical conduction mode, the soft switching of a flyback converter can be achieved. In critical-mode operation, light loads cannot be maintained due to very high switching frequency and the loss of output voltage regulation. A control which regulates the output down to the zero load and

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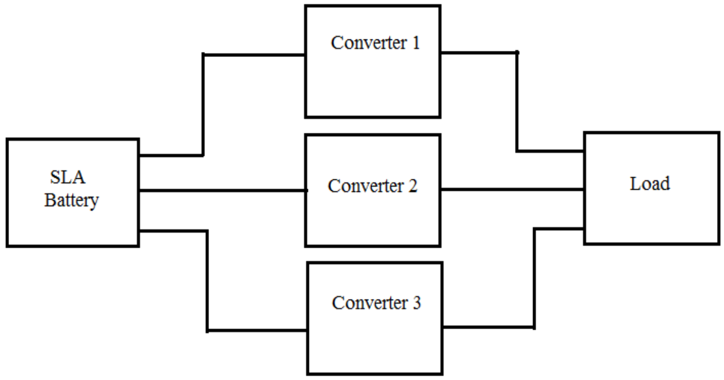

Fig. 1: Block diagram of proposed multi flyback converter

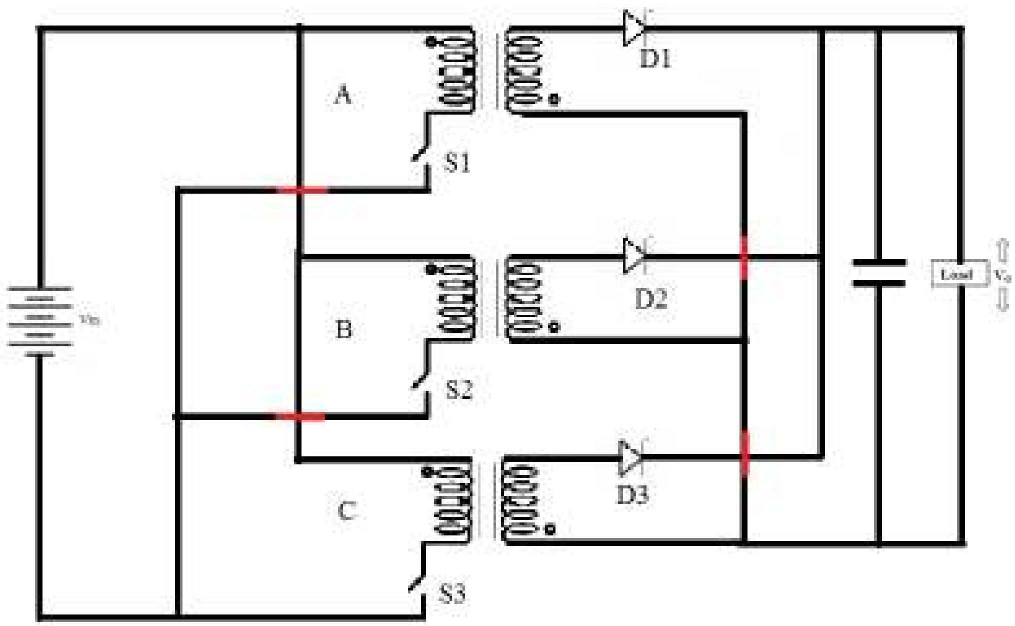

Fig. 2: Simplified circuit diagram of multi flyback converter

maintains soft switching at light loads was proposed in Panov and Jovanovic (2002). A soft switching pulse-width-modulated fly back dc/dc converter with simple circuit was proposed by Majid and Abbas (2013). A multi-output Fly-back converter using a simple circuit for soft switching was proposed in Venkanna *et al.* (2014). This study presents a multi output flyback converter operating in boost mode which acts as an interface for electric vehicle application.

MATERIALS AND METHODS

Multi flyback converter topology: Figure 1 gives the basic block diagram of the proposed Multi Flyback converter. Figure 2 shows the power schematic of the three identical flyback converters connected in parallel. Each converter is connected to a single combination of four Sealed Lead Acid (SLA) battery connected in series and the output of the converter is connected to the common dc bus. If the first converter is considered, then during first mode of operation S1 is active and during second mode D1 is active. During the power flow active switches S1, S2 and S3 get switching pulses of 64% duty cycle when conducting in parallel and simultaneously hence the output is obtained at 33% duty cycle as shown in Fig. 3 and 4 shows the ideal switch voltage and current waveforms assuming Continuous Conduction Mode (CCM) for the power flow.

Flyback converter design: The heart of the circuit is the choke or the inductor. The circuit mainly involves the design of the inductor and the capacitor. The load connected at the output of the converter is a three phase inverter connected to the motor. Thus the capacitor voltage ripple is dominated by the dc-link current ripple of the inverter and capacitor value is decided depending on that ripple. DCM and CRM modes are not

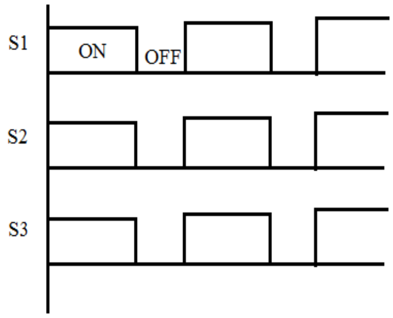

Fig. 3: Parallel switching pulses

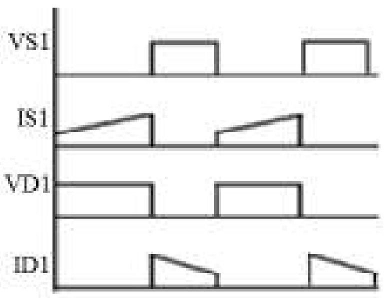

Fig. 4: Ideal switch current and voltage waveform

considered for the design as if the load is very less, then the converter can go into CRM or DCM, similar to any standard flyback converter. Hence only the CCM mode is considered for the design.

The design of flyback converter transformer differ from the other configurations, in this the transformer is addition to the conventional function of energy transfer, also act as an inductor.

In the transformer winding pattern, the primary is wound with thin copper foil adhesive strip separated with mylar sheet in between each layer. The pattern has reduced the spike than that of the former patterns and the leakage has been reduced to 10 µH. This pattern is further implemented in the Multi Flyback topology.

Governing equation of a flyback converter:

$$\frac{Vo}{Vs} = \frac{D}{1\text{-}D}\frac{N2}{N1} \tag{1}$$

Specification: Vs = 48V, Vo = 350V, Fs = 50 kHz, D = 33% (output), Supply ripple = 10%.

Design of single flyback converter:

Po (3 phase) = 750W
Po (1 phase) = 750/3 = 250W
Vs_min = 43.2V, Vs_max = 52.6V

Assume:

$\Delta B = 0.1T$
$\Delta In = 0.75$
$\eta = 0.80$
$\alpha = 0.84$
$Kw = 0.3$
$J = 3e6$
$\frac{\Delta Vo}{Vo} = 1\%$

Output current:

$$Po = Vo \times Io\left(\frac{1\text{-}D}{D}\right) \tag{2}$$

$$250 = 350 \times Io\left(\frac{1\text{-}0.66}{0.66}\right)\ Io = 1.38A$$

Turns ratio:

$$n = \frac{Vo}{Vs_{min}}\left(\frac{1-D}{D}\right) = \frac{350}{43.2}\left(\frac{1-0.66}{0.66}\right) = 17 \tag{3}$$

Primary peak currents:

$$I1_{peak} = \frac{2nI0}{D(2\text{-}\Delta In)} = \frac{2 \times 17 \times 1.38}{0.66(2\text{-}0.75)} = 13.96A \tag{4}$$

Ripple currents:
Primary:

$$\Delta I1 = I1_{peak} \times \Delta In = 13.96 \times 0.75 = 10.47A \tag{5}$$

Secondary:

$$\Delta I2 = \frac{\Delta In}{n} = \frac{0.75}{17} = 2.51A \tag{6}$$

Secondary peak currents:

$$I2_{peak} = \frac{\Delta I2}{\Delta In} = \frac{2.51}{0.75} = 3.33A \tag{7}$$

Area product for incomplete energy transfer:

$$Ap = \frac{Po\left[\left(\frac{1}{\eta}\sqrt{\frac{4D\alpha}{3}}\right) + \sqrt{\frac{4(1-D)\alpha}{3}}\right]}{Kw \times J \times \Delta B \times Fs} = \frac{350\left[\left(\frac{1}{0.80}\sqrt{\frac{4 \times 0.66 \times 0.84}{3}}\right) + \sqrt{\frac{4(1-0.66)0.84}{3}}\right]}{0.3 \times 3e6 \times 0.1 \times 50e3} = 9398.84mm\text{^}4 \tag{8}$$

Choose a suitable core which has an Ap greater than the value calculated above.

Core selection: EE65/33/28:

$Ap = Aw \times Ac$
$G = \frac{D-E}{2}$
$Aw = 2 \times G \times F$

Table 1: Specification

Nominal battery voltage	48 V
Nominal output voltage	300 V
Switching frequency	50 kHz
Output power	750 W
Duty cycle	33%
Primary inductance	546 μH
Turns ratio	17
Switches	MOSFET

$\mathrm{Ac} = \mathrm{E} \times \mathrm{F}$
Ap = 2385356 mm^4, Aw = 537.2 mm^2
Ac = 444 mm^2

RMS currents:
Primary:

$$\mathrm{I1rms} = \sqrt{\frac{(\mathrm{D})\left[\Delta \mathrm{I1}^2+\frac{3}{4}\left(\left(\frac{2\mathrm{nIo}}{\mathrm{D}}\right)^2-\Delta \mathrm{I1}^2\right)\right]}{3}} \quad (9)$$

$$= \sqrt{\frac{(0.66)\left[10.47^2+\frac{3}{4}\left(\left(\frac{2\times17\times1.38}{0.66}\right)^2-1.47^2\right)\right]}{3}} \quad (10)$$

I1rms = 7.49A

Secondary:

$$\mathrm{I2rms} = \sqrt{\frac{(1\text{-}\mathrm{D})\left[\Delta \mathrm{I2}^2+\frac{3}{4}\left(\left(\frac{2\mathrm{Io}}{1\text{-}\mathrm{D}}\right)^2-\Delta \mathrm{I2}^2\right)\right]}{3}} \quad (11)$$

$$= \sqrt{\frac{(1\text{-}0.66)\left[2.51^2+\frac{3}{4}\left(\left(\frac{2\times1.38}{1\text{-}0.66}\right)^2-2.51^2\right)\right]}{3}}$$

I2rms = 2.40A

No. of turns:
Primary:

$$\mathrm{N1} = \frac{\mathrm{Vs\_max}\times\mathrm{D}}{\Delta\mathrm{B}\times\mathrm{Ac}\times\mathrm{Fs}} = \frac{52.6\times0.66}{0.1\times444\mathrm{e}\text{-}6\times50\mathrm{e}3} = 16 \quad (12)$$

(Taking the nearest higher integer if the value turns out to be real).

Secondary:

$$\mathrm{N2} = \mathrm{n}\times\mathrm{N1} = 17\times16 = 67 \quad (13)$$

Wire gauge selection:

$$\mathrm{a1} = \frac{\mathrm{I1rms}}{\mathrm{J}} = \frac{7.49}{3\mathrm{e}6} = 2.49\ \mathrm{mm\hat{}2} \quad (14)$$

Choose the wire gauge whose cross section is greater than that calculated above:

SWG 15 (2.62 mm^2)

$$\mathrm{a2} = \frac{\mathrm{I2rms}}{\mathrm{J}} = \frac{2.40}{3\mathrm{e}6} = 0.80\ \mathrm{mm\hat{}2} \quad (15)$$

Choose the wire gauge whose cross section is greater than that calculated above:

SWG 19 (0.81 mm^2)

Cross check:

$$\mathrm{Aw}\times\mathrm{Kw} \geq \sum_{i=1}^{m} \mathrm{ai}\times\mathrm{Ni} \quad (16)$$

Using the actual values of cross section we have:

Aw×Kw = 161.16
$(a1 \times N1) + (a2 \times N2) = 96.16$

So, the inequality is satisfied, which means that the winding will fit in the available window area.

Primary inductance:

$$\mathrm{L1} = \frac{\mathrm{Vs_{min}}\times\mathrm{D}}{\Delta\mathrm{I1}\times\mathrm{Fs}} = \frac{43.2\times0.66}{10.47\times50\mathrm{e}3} = 546\ \mu\mathrm{H} \quad (17)$$

Air gap length: Lg to be found out from the basic equation:

Flux = mmf/reluctance

$$\mathrm{Lg} = \frac{\mu0\times\mathrm{N1}^2\times\mathrm{Ac}}{\mathrm{L1}} = \frac{4\pi10\mathrm{e}\text{-}7\times16^2\times444\mathrm{e}\text{-}6}{546\mathrm{e}\text{-}6} = 2.62 \quad (18)$$

Load resistance:

$$Ro = \frac{Vo}{I0} = \frac{350}{1.38} = 253\Omega \quad (19)$$

DC link capacitor:

$$\frac{\Delta Vo}{Vo} = \frac{D}{RCFs} = C = \frac{0.1\times0.66}{253\times50e3} = 5\mu F \quad (20)$$

The Table 1 gives the parameters for the design of Multi Flyback converter.

EXPERIMENTAL RESULTS

The designed flyback converter experimental results are given in this section. The carrier signal is shown in Fig. 5. The switching pulses obtained from 16 pin PWM IC TL 494 are shown in Fig. 6. PWM pulse from TL494 during switching are shown in Fig. 7. The driver circuit and Multi Flyback Converter is shown in Fig. 8. IR2110 driver IC is used and the output pulses from IR2110 are shown in Fig. 9. The output diode voltage and the Converter output voltage during soft starting and resistive loading are shown in Fig. 10 and 11, respectively.

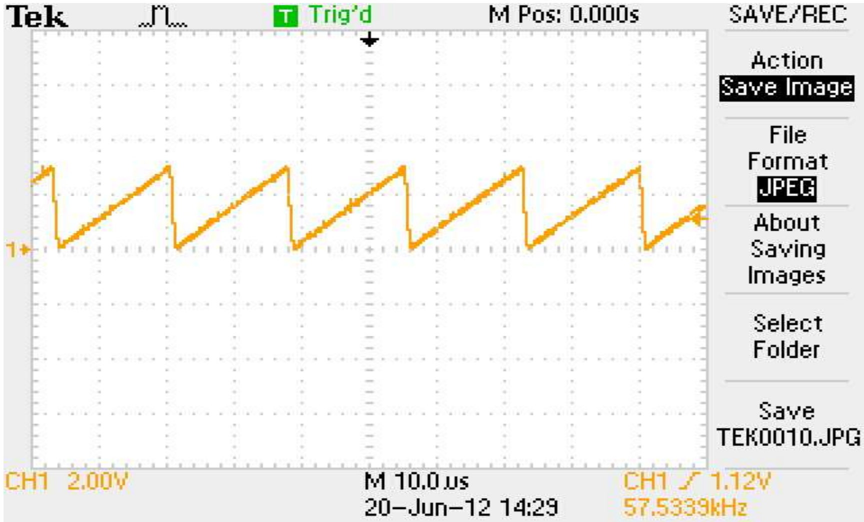

Fig. 5: TL494 sawtooth waveform

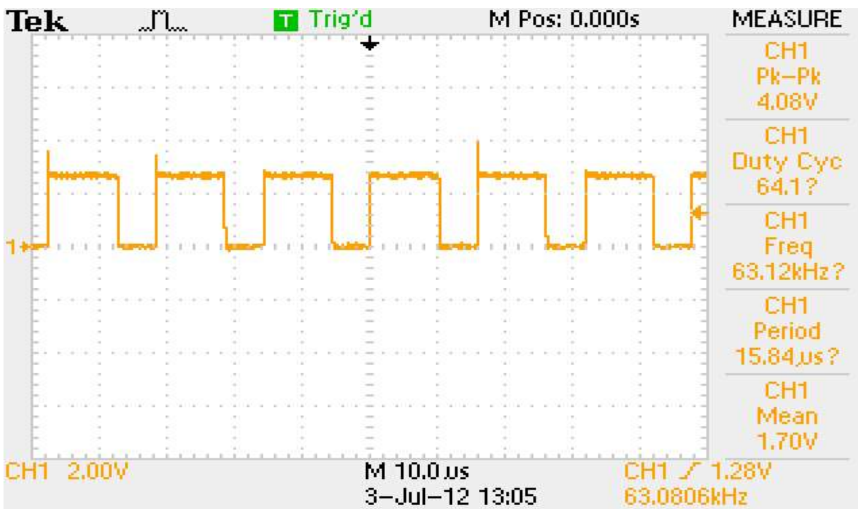

Fig. 6: PWM pulse from TL494

Fig. 7: PWM pulse from TL494 during switching

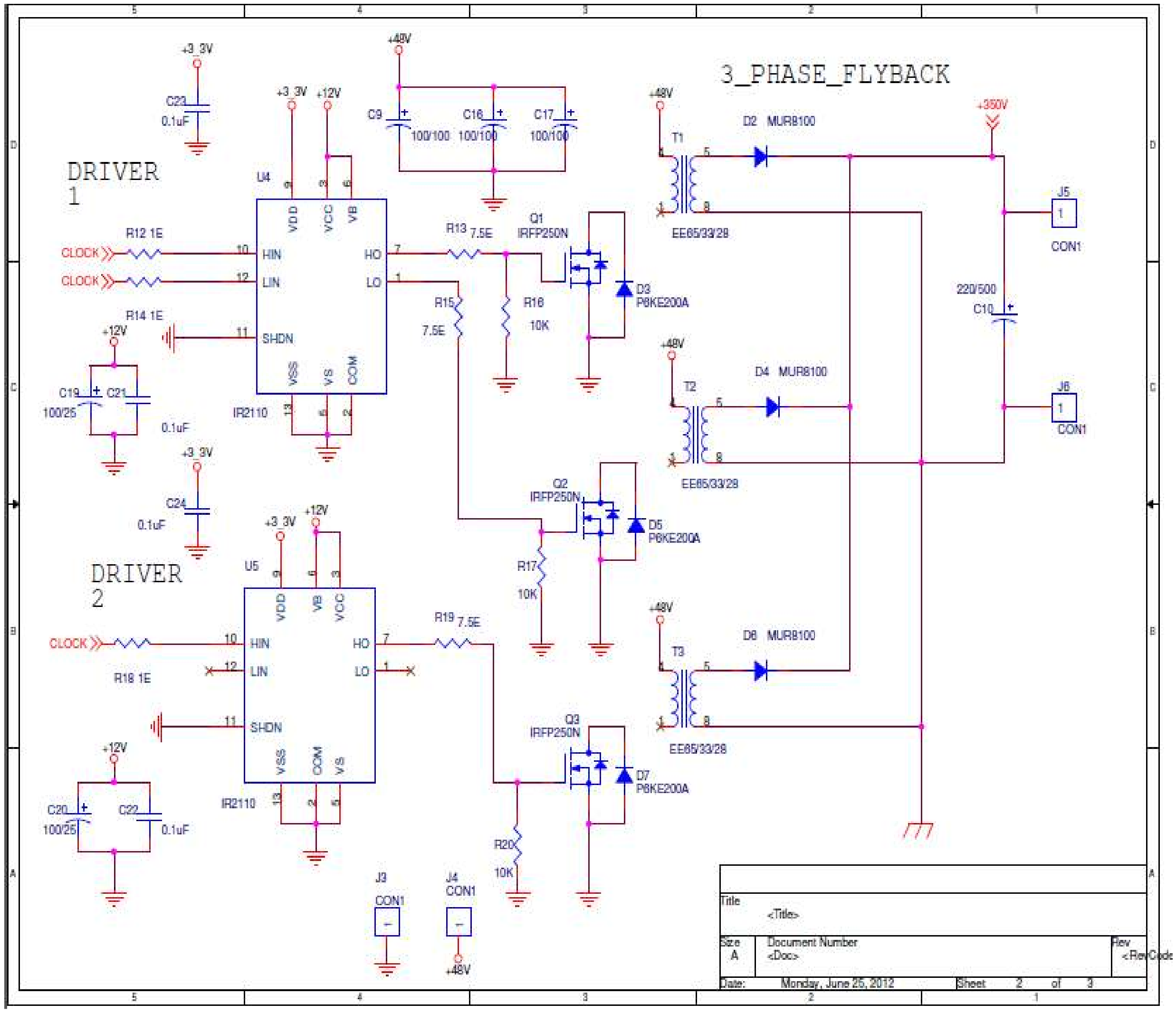

Fig. 8: Driver circuit and multi flyback converter

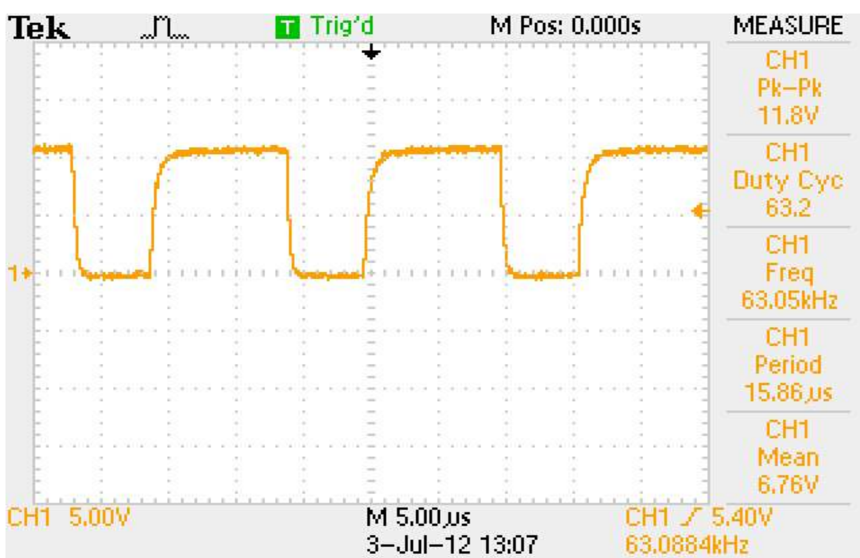

Fig. 9: Gate pulse from IR2110

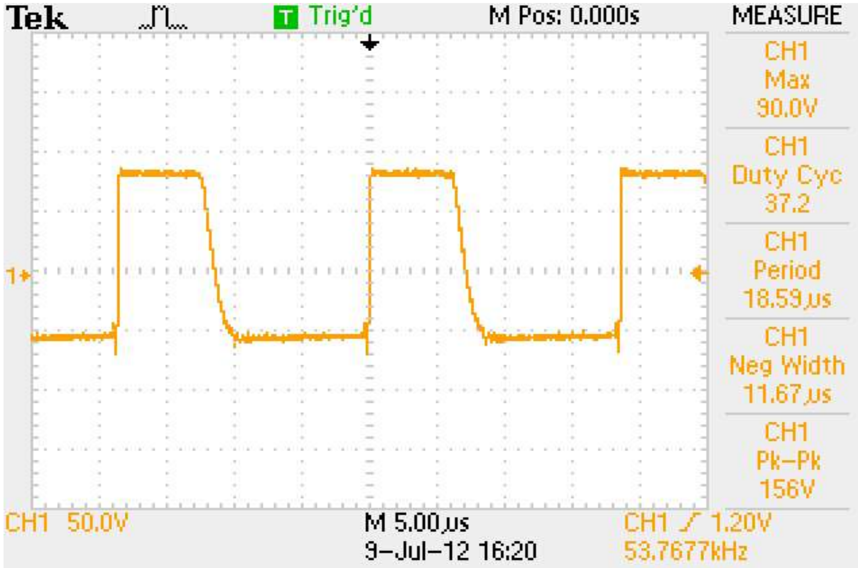

Fig. 10: Output diode voltage

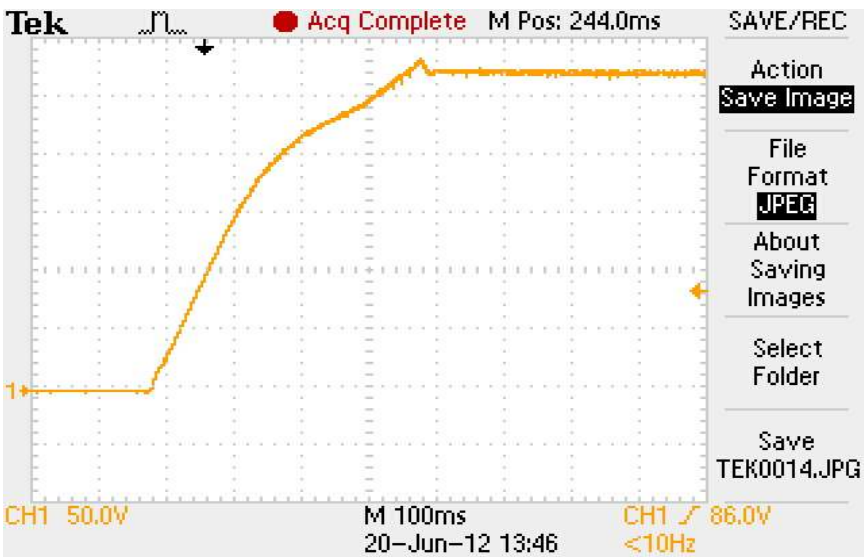

Fig. 11: Converter output voltage during soft starting and resistive loading

CONCLUSION

Conventional flyback converters are usually modeled for the buck mode of operation. But to operate the converter in step up mode i.e., in boost mode with high turns ratio is complex. The inductor winding and coupling should perfect enough to reduce the effect of leakage or stray inductance, hence the stress across the switch. The Multi flyback dc-dc converter proposed serves the role of an interface for electric and hybrid electric vehicle applications. Because the three converters operating in parallel with fixed 64% duty cycle of operation, the capacitor ripple current is also reduced. The transformer design technique reduces the leakage inductance to some extent and eliminates the requirement of snubber. Furthermore, it should be noted that the interface could be made between any given battery voltage and dc-link voltage by only tuning the turns ratio of the flyback transformers. The scheme is experimentally verified and the experimental results are presented. When it comes to the analysis of dc-dc converter, efficiency is a major factor of concern. Because the proposed converter is a hard-switched one, the efficiency is definitely less than that of soft-switched converters. However, the reduction in leakage inductance limited the losses mostly to switching and conduction losses to some extent.

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