Analysis of an Interleaved Flyback Converter Featured with Zero-Voltage Transition

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***Abstract*— The flyback converters are widely used in DC-DC power supplies in the small power areas because of its simple structure and robust characteristics. The multiple output and cost effective design makes the flyback converter attractive. The major disadvantage of flyback converter is the hard switching operation which results in a high switching loss, high EMI noise, and high switch voltage stress. To overcome these drawbacks, various kinds of soft switching techniques have been proposed. This paper presents an interleaved flyback converter, which is remarked with ZVS (Zero Voltage Switched) active switches and reduced reverse-recovery loss on the rectifying diodes. This converter can provide up to 500W power with the highest efficiency as high as 91%. In addition, burst-mode control is provided to drive the converter at low load.**

***Index Terms*— Zero Voltage Switching (ZVS), Zero Current Switching (ZCS), Switched Mode Power Supply**

I. INTRODUCTION

For reasons of simple structure and robust characteristics, the flyback converter has been one of the most widely used dc-dc power supplies in the small power areas. The multiple-output and cost effective design makes the flyback converter attractive for applications such as personal computers, assorted home appliances, and various office equipments, etc. Major disadvantage of flyback converter attributes to the hard switching operation. In general, the hard switching operation of the power switch results in a high switching loss, high EMI noise, and high switch voltage stress. To overcome these drawbacks, various kinds of soft switching techniques have been proposed.

Among them, the active-clamp flyback converters make use of simple active clamp network to achieve ZVS operation of the power switches. However, the power switch still suffers from high voltage stresses since the sum of input voltage and the transformer primary voltage is imposed on them. Therefore, the asymmetrical half bridge flyback converters, which utilizes the half bridge structure and a blocking capacitor to achieve ZVS operation of the power switches as well as low switch voltage stresses, are gaining popularity. From previous works, it had been shown that, by reducing the magnetizing inductor and allowing duty cycle constraint beyond 50%, the half bridge flyback converter can achieve ZVS operation for power switches from no load to full load conditions. However, the rectifier diode suffers from high di/dt at turn off, which results in significant energy loss from high reverse recovery current.

In the same power circuit, but added an inductor at the rectifier to obtain the same secondary diode current waveforms as the conventional forward converter does. The output rectifier is complex and has no soft switching operations as well. In this research, a half bridge forward/flyback converter without using output inductor is proposed, in which both the power switches and output power diode can achieve soft switching operations. The voltage stress of power switches is not greater than the input voltage.

ZVS is used to turn the power switches and ZCS can be used to turn on and off the output diode. The ZVS and ZCS conditions can be maintained for the full spectrum of the load range. The characteristics of the proposed converter rely on the utilization of resonant inductor and blocking capacitor as resonant energy delivery devices rather than a pair of linearly charging and discharging components. The operational principles, circuit analysis, and design equations of the proposed converter are described in this report. The experimental test of a prototype converter is performed and the test results are presented to confirm the validity of the proposed converter.

Flyback converters are widely applied on electrical power-supply circuits with low-power demand, but requesting electrical isolation due to their simple structures and low component counts. The limited power-handling capability is ascribed to this converter's buck–boost-based behavior. The active switch bears the voltage sum of the input and output ends, which makes the switching loss higher than the other converters. Besides, the inductor-behaved transformer claims for an adequate air gap in the core to store enough energy without magnetic saturation. This air gap increases the leakage inductance on both sides of the transformer, which brings about lower power efficiency and higher voltage stress on switching components.

Two fly back converters are parallel-connected both at input and output ports in addition to an auxiliary inductor connected with the two rectifying diodes of each converter. By this arrangement, both the active switches are featured with ZVS, while the rectifying diodes are smoothly cut off and are with the reduced reverse-recovery loss. The Fly back converter belongs to the primary switched converter family, which means there is isolation between in and output. Fly back converters are used in nearly all mains supplied electronic equipment for low power consumption, up to approximately 300W.

II. CONVENTIONAL FLYBACK CONVERTER

Flyback converters are widely applied on electrical power-supply circuits with low-power demand, but requesting electrical isolation due to their simple structures and low component counts. The limited power-handling capability is ascribed to this converter's buck–boost-based behavior. The active switch bears the voltage sum of the input and output ends, which makes the switching loss higher than the other converters.

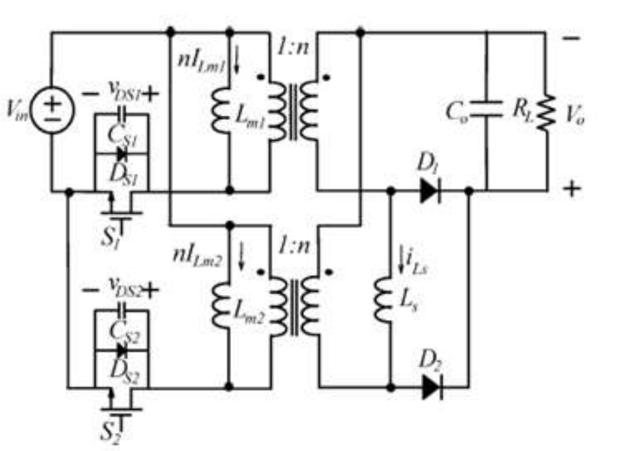

Fig 1: Conventional Interleaved Flyback converter

Modes of Operation:

The circuit operation is divided into eight modes. The former four modes define the ON state to turn - OFF transient of S1, while S2 undergoes OFF-state to zero-voltage turn - ON transition. The latter four modes are similar counterpart with the interchanged roles of S1 and S2. They are detailed as followed.

Mode 1 [t0 < t < t1]:

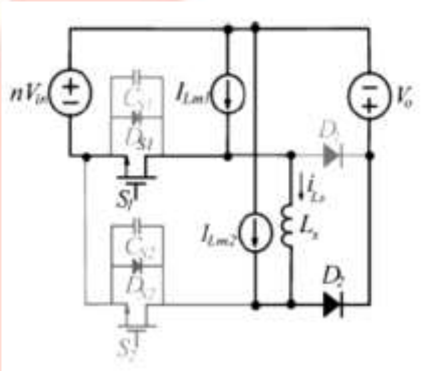

Fig 2 Mode 1 [t0 < t < t1]

Before t0, VGS1 has been pulled high and switch S2 has already been turned off. At t0, voltage across S2 , VDS1 , rises up to nVin + Vo and turns diode D2 ON, which causes the current originally flowing through S2 detours to D2 and energize the load. Meanwhile, current through S1 Is1 ramps up from negative and crossing zero at this instant. During Mode I, both S1 and D2 are in the conduction state, thus inductor Ls will bear a voltage of nVin + Vo, which results in linear decrease of current iLs at a slope of (nVin + Vo)/Ls and linear increase of Is1. As iLs falls down to zero, ILm1 passes through S1 completely. From this moment on, iLs reverses, and iLm2 travels via Ls to pass through S1. At the end of this mode, iD2 ceases and is1 is the sum of iLm1 and iLm2. Since iD2 ramps down to zero in this topology, instead of being abruptly turned off as traditional flyback converter, the reverse-recovery loss in this topology is greatly alleviated.

Mode 2 [t1 < t < t2]:

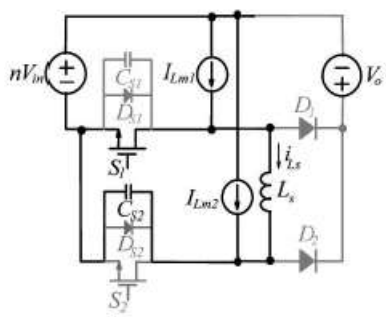

Fig 3 Mode 2 [t1 < t < t2]

Since diode D2 is OFF, capacitance Cs2 is no longer clamped at the voltage level of nVin + Vo. The stored energy in Cs2is able to be released by the resonance of this capacitance with Ls. When voltage VDs2 oscillates to zero, the next mode is entered.

Mode 3 [t2 < t < t3]:

At t2, voltage VDs2 declines to zero; however, the inductor current iLs does not rest and continues flowing through the antiparallel diode Ds2 of S2.

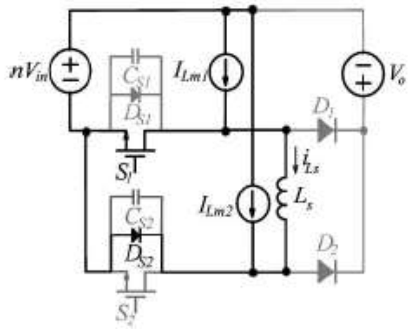

Fig 4 Mode 3 [t2 < t < t3]

The inductor current freewheels through S1 and Ds2 under the assumption of zero-voltage drops on switches and diodes. Current iLs is kept constant throughout this mode. It should be noticed that the conduction of Ds2 holds the voltage across S2 at zero level, which provides an adequate interval for ZVS on S2.

Mode 4 [t3 < t < t4]:

At the onset of this mode, switch S1 is turned off and forces currents iLm1 and iLs to bypass through capacitor Cs1. This bypassing transfers energy from inductors to Cs1 and slightly reduces the magnitude of iLs.

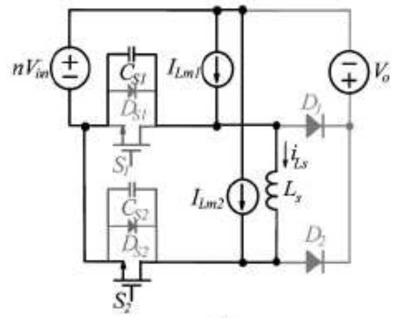

Fig 5 Mode 4 [t3 < t < t4]

When voltage VDs1 rises to nVin + Vo, D1 is forward-biased and initialize the next mode. As it was earlier stated, the following Modes V–VIII imitate the similar scenario to zero-voltage switch on S1.

III. PROPOSED FLYBACK CONVERTER

For reasons of simple structure and robust characteristics, the flyback converter has been one of the most widely used dc-dc power supplies in the small power areas. The multiple-output and cost effective design makes the flyback converter attractive for applications such as personal computers, assorted home appliances, and various office equipment, etc. The major disadvantage of flyback converter attributes to the hard switching operation. In general, the hard switching operation of the power switch results in a high switching loss, high EMI noise, and high switch voltage stress.

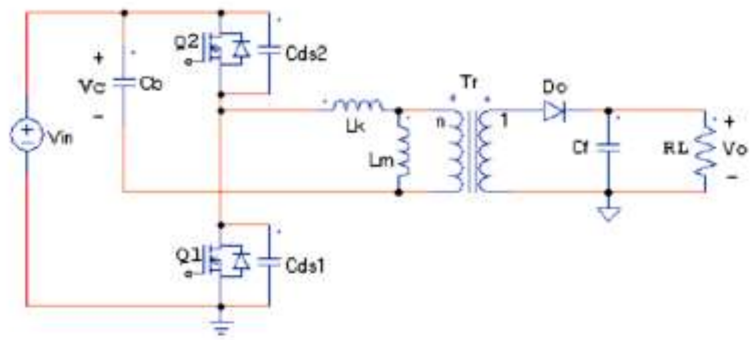

Fig 6 Proposed flyback converter

To overcome these drawbacks, various kinds of soft switching techniques have been proposed. Among them, the active-clamp flyback converters make use of simple active clamp network to achieve ZVS operation of the power switches. By reducing the magnetizing inductor and allowing duty cycle constraint beyond 50%, the flyback converter can achieve ZVS operation for power switches from no load to full load conditions.

Operational Principles:

Figure 6 shows the simplified circuit diagram of the proposed flyback converter. The resonant inductor L_k consists of total leakage inductance of transformer Tr and external stray inductances. The ESRs in passive components and internal resistance of semiconductors are not included in the diagram for simplification. Figure 7 to 14 shows the eight operating modes of the converter during a switching cycle. Prior to describing the basic operational principles, several assumptions are made first:

- The converter is operating in steady state.
- The resonant inductor L_k is much less than L_m.
- The resonant period of C_b and L_k is comparable with the off-time of switch Q_1.
- In mode 2 and 6, the circuit is assumed to behave linearly.
- In mode 3, the resonant current is assumed to be the same as the magnetizing current.

Modes of Operation:

The circuit operation is divided into eight modes. The former four modes define the ON state to turn-OFF transient of Q_1, while Q_2 undergoes OFF-state to zero-voltage turn-ON transition.

Mode 1 (t_0-t_1):

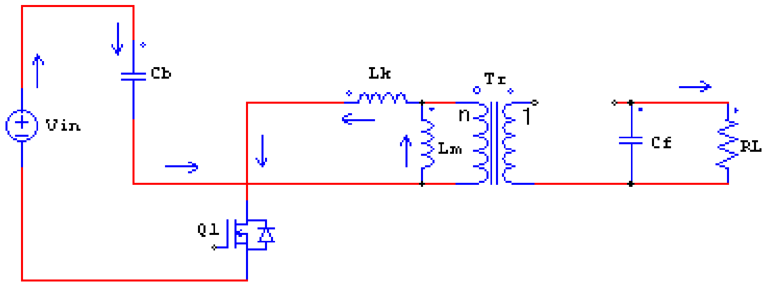

Fig 7 Mode 1(t_0-t_1)

At t_0, Q_1 is on and Q_2 is off. The output diode D_0 is reversely biased. Components C_b, L_m and L_k form a series resonant tank with voltage source V_{in} providing the input energy. Since the length of time interval (t_1-t_0) is short compared with the time constant of the resonant tank, the power source V_{in} charges C_b, L_m and L_k in a linear fashion. The leakage and magnetizing currents start to decrease from zero. This mode ends when Q_1 turns off.

Mode 2 (t_1-t_2):

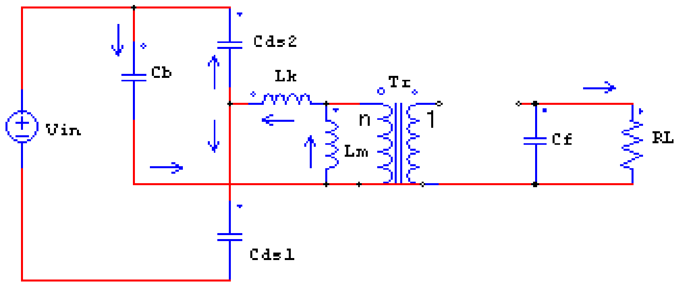

Fig 8 Mode 2 (t_1-t_2)

At t_1, Q_1 is turned off and Q_2 remains off. The components C_b, L_m, L_k and C_{Ds1} form a new series resonant network, and C_b, L_m, L_k and C_{Ds2} form another series resonant network. The power source V_{in} charges C_{Ds1} and C_b with half of the magnetizing current. The other half of the magnetizing current charges C_b through discharging C_{Ds2}.

Mode 3 (t_2-t_3):

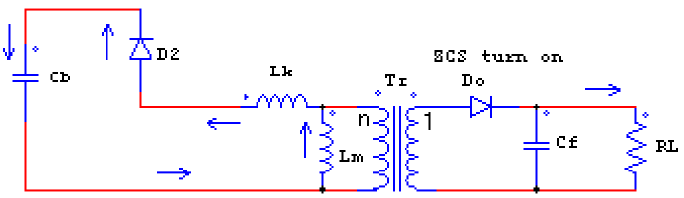

Fig 9 Mode 3 (t_2-t_3)

In this period, both Q_1 and Q_2 are remaining off. The body diode of Q_2 starts to conduct and the voltage across the magnetizing inductor changes polarity. Since the difference between the resonant current and the magnetizing current is zero at this stage, the output diode is not conducting and no voltage is reflected from the converter output to the primary side of transformer. This mode ends when Q_2 is ZVS turned on and the dead time is over.

Mode 4 (t_3-t_4):

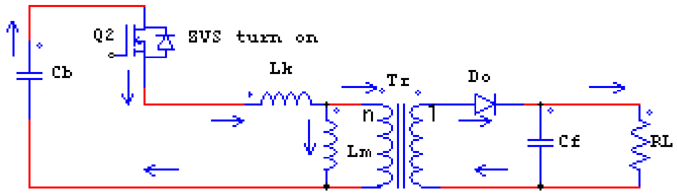

Fig 10 Mode 4 (t_3-t_4)

In this period, Q_2 is on and Q_1 is off. The output diode is conducting and the converter output voltage is reflected to the transformer primary side. The resonant tank formed by C_b, L_m and L_k starts to develop resonant current which deviates the resonant current from the magnetizing current. It is the difference between the resonant current and the magnetizing current that determines the output diode current. This mode ends when the resonant current oscillates down to meet the magnitude of the magnetizing current and the output diode turns off with zero current.

Mode 5 (t_4-t_5):

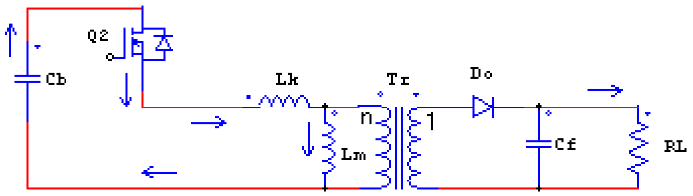

Fig 11 Mode 5 (t_4-t_5)

In this mode, states of Q_2 and Q_1 remains the same as in mode 4. The resonant network stops resonance because the resonant current cannot be less than the magnetizing current. The output diode is forwardly biased with zero current conducted. This mode ends when Q_2 is turned off.

Mode 6 (t_5- t_6):

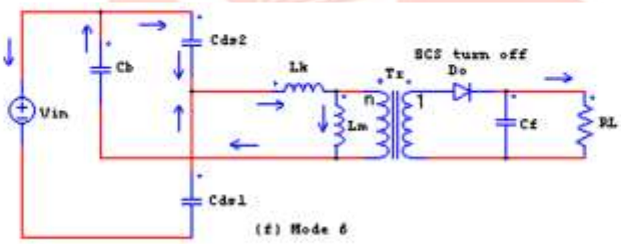

Fig 12 Mode 6 (t_5- t_6)

In this period, Q_1 and Q_2 are both off. At t_5, half of the magnetizing current starts to charge C_{Ds2} from zero voltage, the other half discharges C_{Ds1} from voltage V_{in}. This mode ends when V_{Ds1} drops to $-V_{fd}$ and the body diode of Q_1 starts to conduct.

Mode 7 (t_6 - t_7):

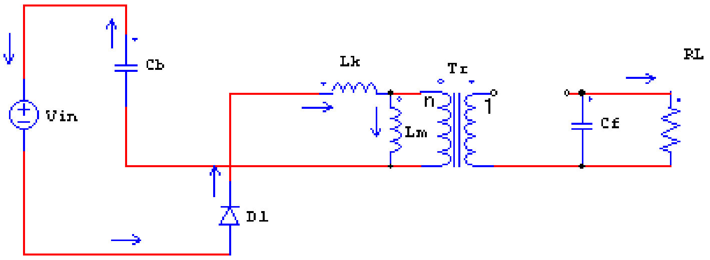

Fig 13 Mode 7 (t_6 - t_7)

In this mode, both Q_1 and Q_2 are still off. At t_6, the voltage across the magnetizing inductor changes polarity. The body diode of Q_1 starts to conduct and the magnetizing current starts to decrease. This mode ends when the dead time is over and Q_1 is ZVS turned on.

Mode 8 (t_7 - t_0):

At t_7, Q_1 turns on under ZVS. The magnetizing current keeps decreasing in a linear fashion and C_b discharges energy back to the voltage source V_{in}. This mode ends when the magnetizing current decreases to zero. Then the input power source begins to charge
C_b, L_m and L_k again, and another switching cycle repeats.

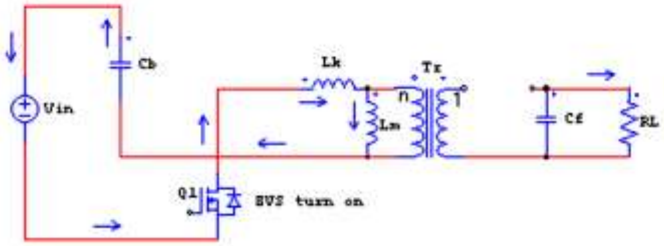

Fig 14 Mode 8 (t_7 - t_0)

The modes of operation in the proposed method are explained in detail. It is used to reduce the drawback of the conventional method. Instead of two transformers, a single transformer is used to reduce the overheat. Based on the design consideration in the preceding section, a prototype converter operated at the frequency of 50 kHz has been constructed. The ZVS and ZCS conditions can be maintained for the full load range.

IV. SIMULATION RESULTS

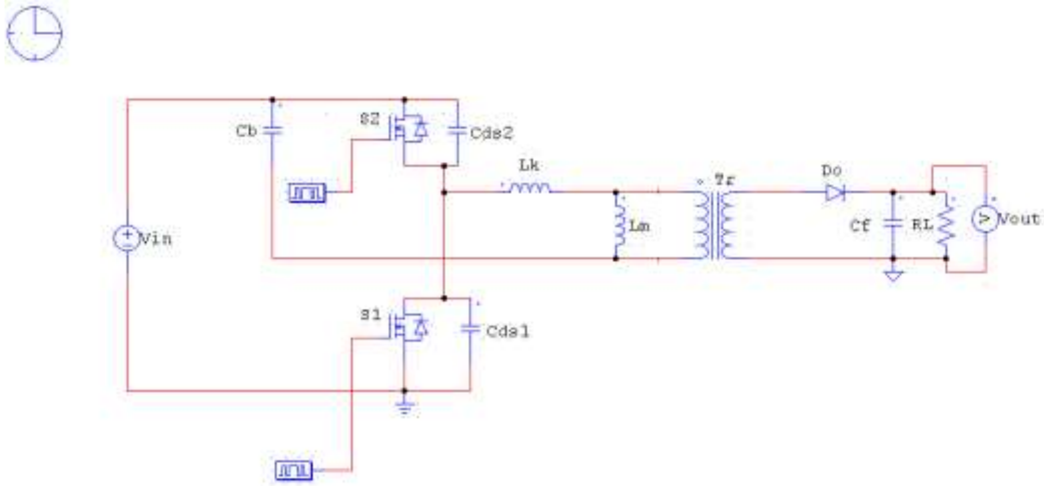

Fig 15 PSIM Simulation diagram for open loop proposed flyback converter

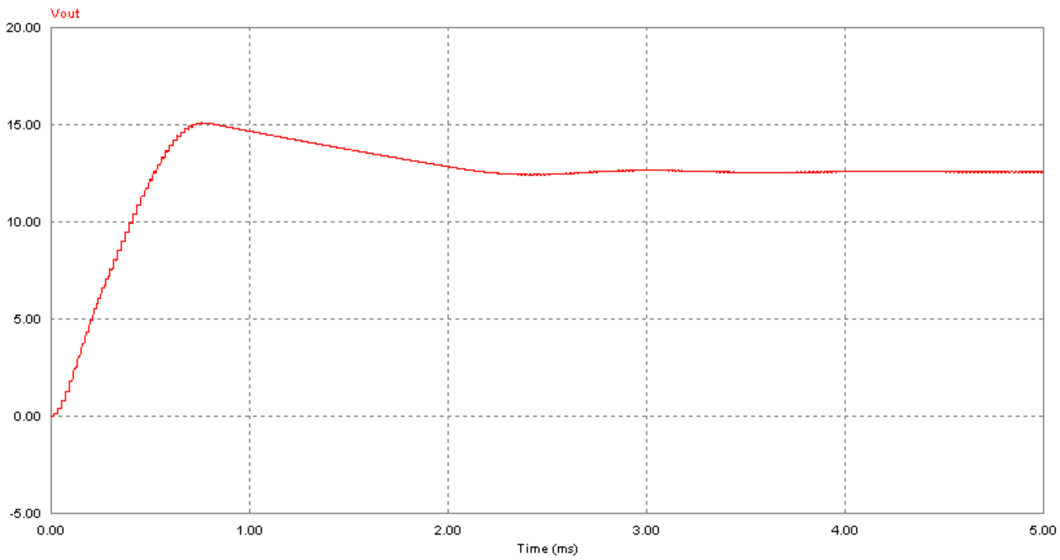

Fig 16 Output voltage for open loop

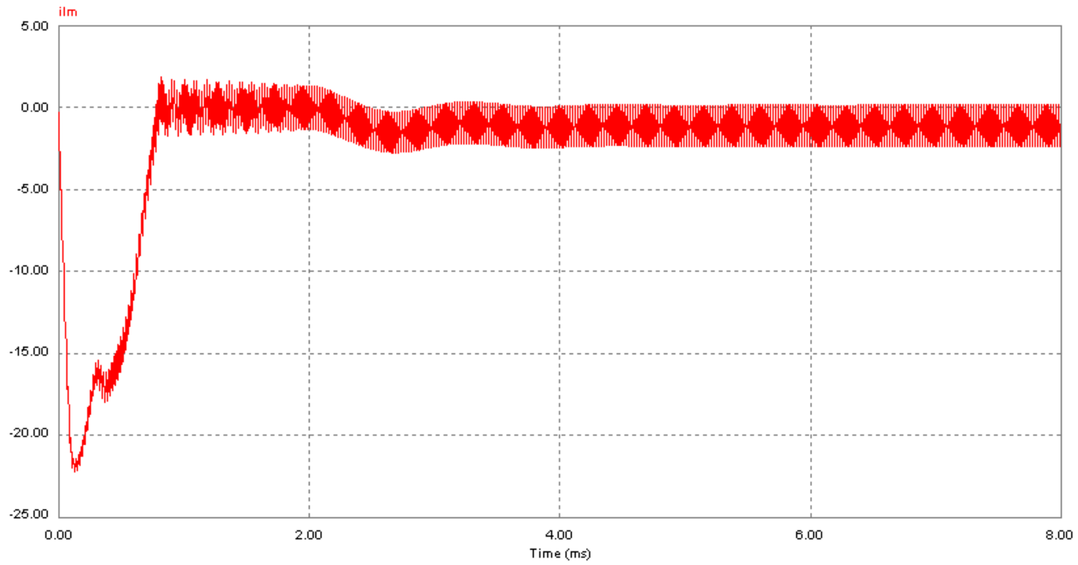

Fig 17 Magnetising inductance current for open loop

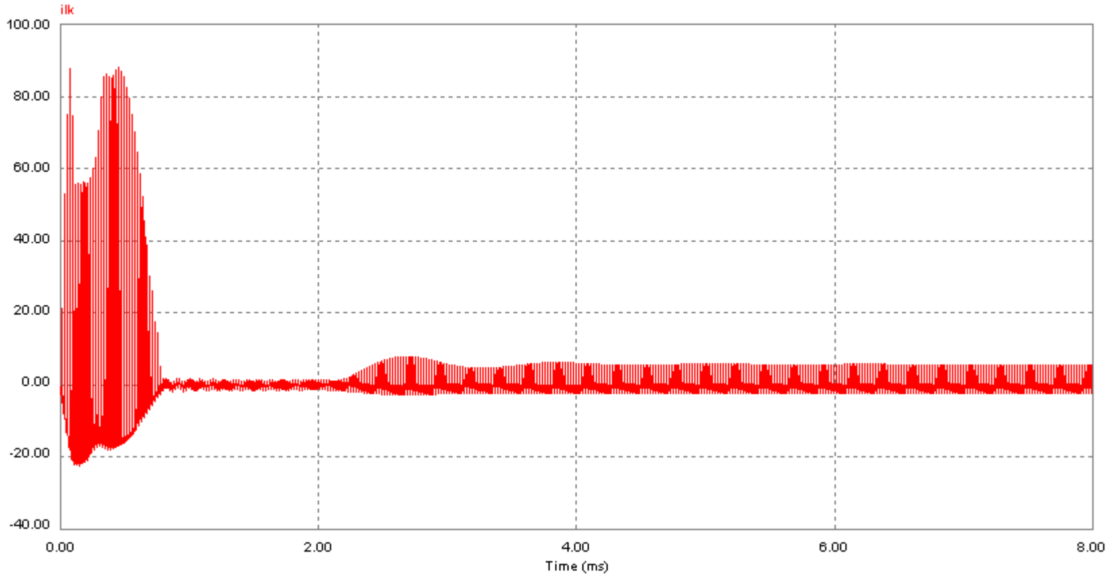

Fig 18 Resonant inductance current for open loop

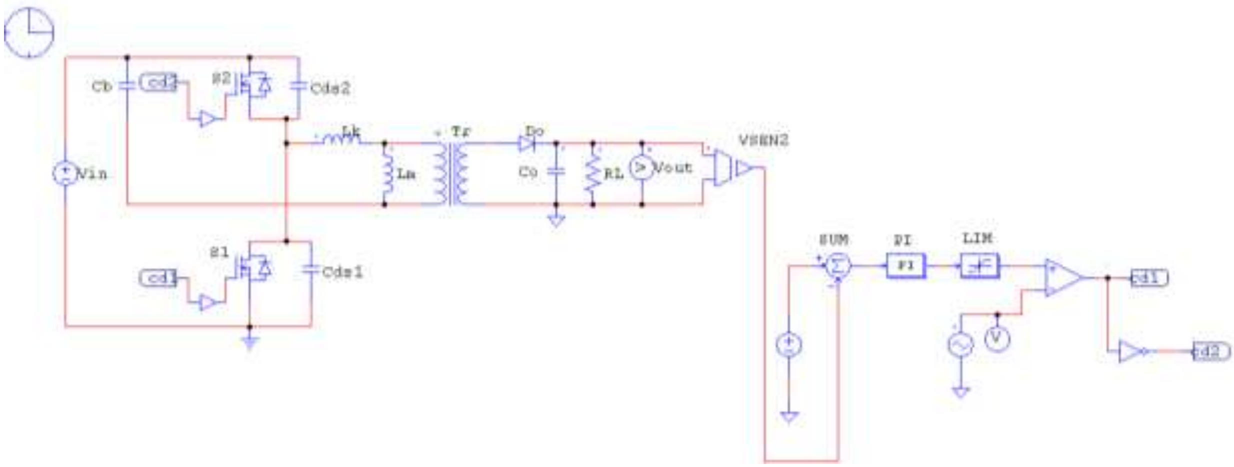

Fig 19 PSIM Simulation diagram for closed loop proposed flyback converter

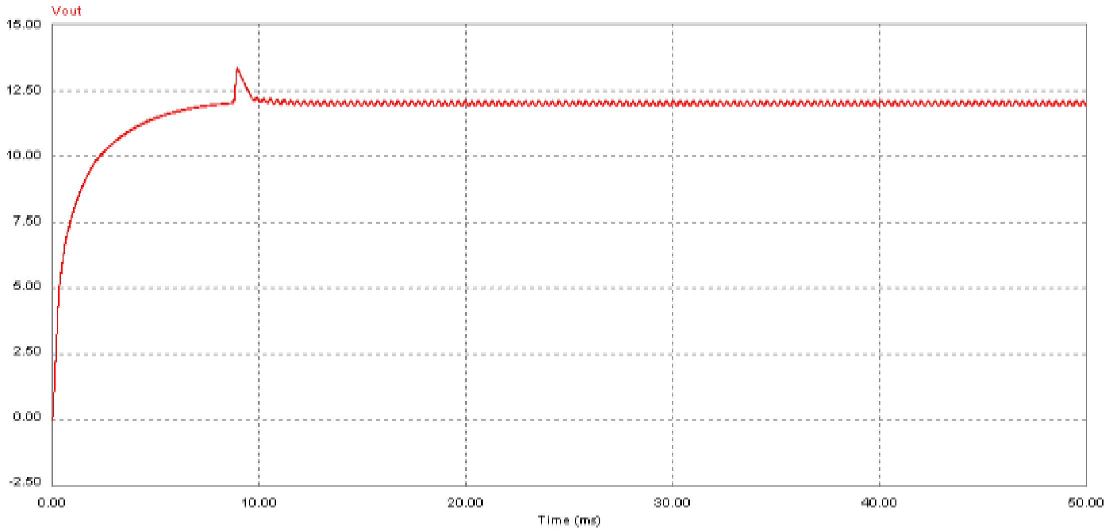

Fig 20 Output voltage for closed loop

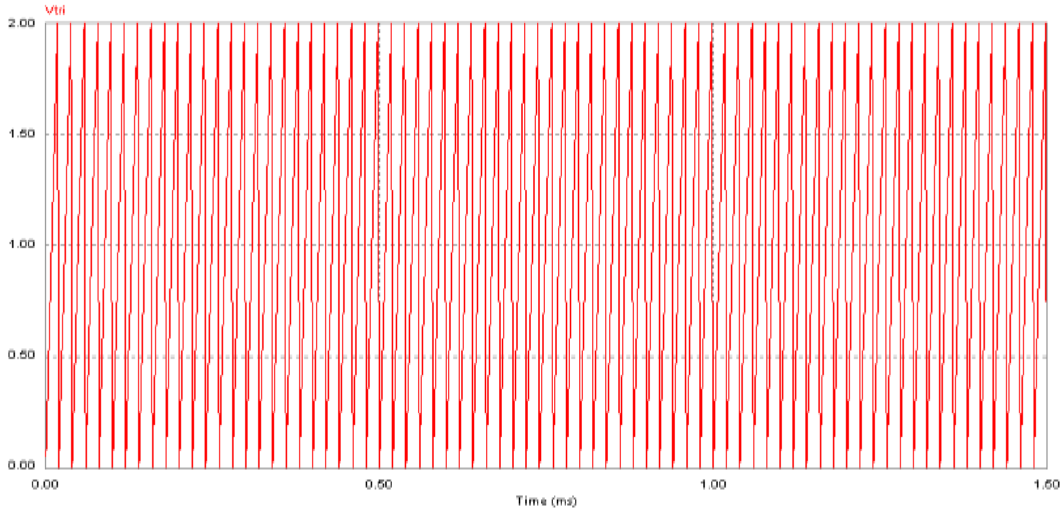

Fig 21 Triangular wave voltage for closed loop

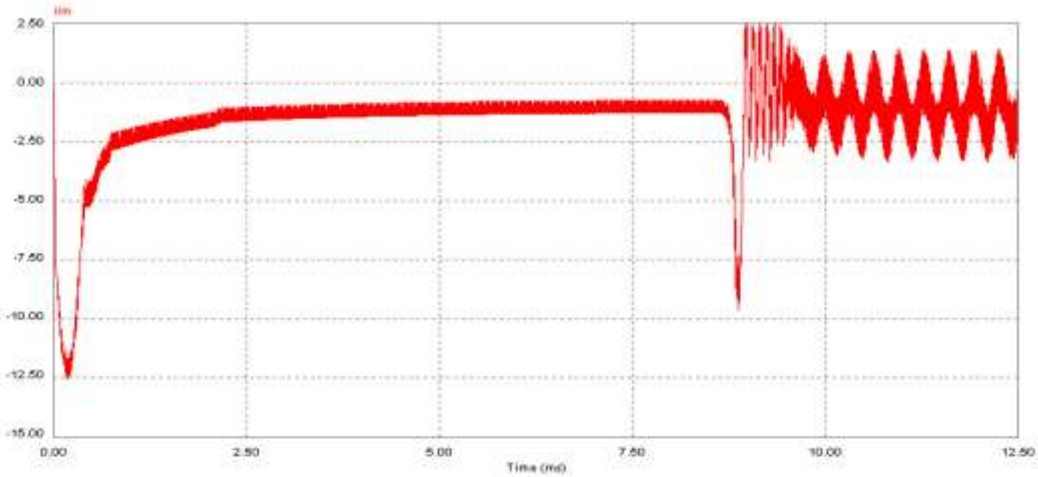

Fig 22 Magnetising inductance current for closed loop

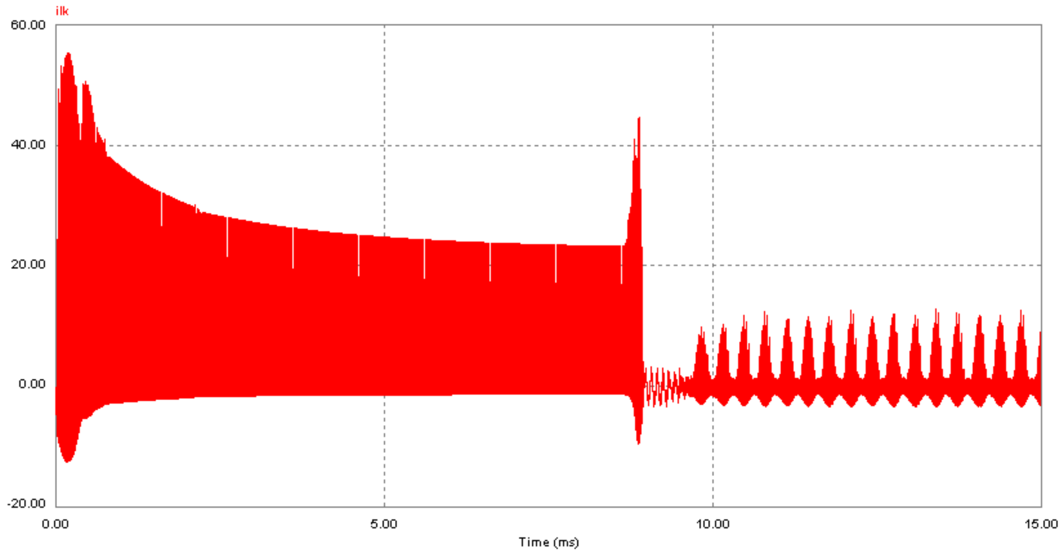

Fig 23 Resonant inductance current for open loop

CONCLUSION:

This paper has presented the analysis and experimental results of a flyback converter without output inductor. ZVS is used to turn on the power switches and ZCS is used to turn on and off the output diodes. It has been found that the ZVS operation of the power switches is obtained from the magnetizing current, the ZCS operation of the output power diode is achieved from the resonant current. The ZVS and ZCS conditions can be maintained for the full load range. The operational principles have been presented in the mode analysis, and the design equations have been derived in steady state analysis. The necessary conditions for ZVS and ZCS operations have been obtained as well. This converter can provide up to 500W power with the highest efficiency as high as 91%. Even at 50-W output, this converter yields efficiency higher than 83%.

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