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ZCS-PWM Converter for Reducing Switching Losses

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Abstract: *Zero-current (ZC) switching pulse-width modulated (PWM) fly back DC-DC converter is an extended version of the single switch fly back converter with an auxiliary circuit. The main switch and auxiliary switch operate at ZCS turn-on and turn-off conditions, and all uncontrolled devices in the converter operate at zero-voltage-switching (ZVS) turn-on and turn-off. Soft switching techniques are used in PWM DC-DC converters to reduce switching losses and electromagnetic interference (EMI). The circulating current for the soft switching flows only through the auxiliary circuit, the conduction loss and current stress of the main switch are minimized. The general principle of operation of ZCS flyback converter, its merits and demerits, experimental setup and results has been summarized.*

Keywords: *Flyback converter, Auxillary circuit, zero current switching(zcs),experimental setup and results.*

I. Introduction

A typical DC-DC converter is comprised of active switches such as MOSFETs or IGBTs, diodes, magnetic components such as inductors and transformers, and static devices such as capacitors. Magnetic components are heavier and occupy more volume than any other parts in a power electronic converter. The size of the magnetic components is inversely proportional to the switching frequency of the converter. In order to decrease the volume and weight of a DC-DC converter, higher switching frequency must be chosen. Increasing the switching frequency leads to increased switching losses which in turn reduces the converter efficiency. Soft switching techniques are used in PWM DC-DC converters to reduce switching losses and electromagnetic interference (EMI).

The pulse width modulation (PWM) technique is highly regarded for its high power capability, fast transient response and ease of control. PWM dc–dc converters have been widely used in industry. Among these dc/dc converters, the flyback topology is the most attractive because of its relative simplicity compared with other topologies used in low power applications. The flyback transformer serves the dual purpose of providing energy storage as well as converter isolation, theoretically minimizing the magnetic component count when compared with the forward converter. Flyback converters are isolated versions of buck-boost converters and are widely used in low to medium power applications. They are relatively simple and have very few components.

The paper discusses about a novel ZCS-PWM flyback converter with a simple ZCS-PWM auxiliary circuit. All semiconductor devices are operated at ZCS turn-on and turn-off condition. It does not require a floating and an isolated driver for the auxiliary switch to decrease the complexity of the control circuit, since the two switches have a common ground. Since the circulating current for soft switching flows only through the auxiliary circuit, the conduction loss and current stress of the main switch are minimized. In addition, at constant frequency and with reduced commutation losses, the new ZCS-PWM flyback converter has no additional current stress and conduction losses in the main switch compared to its hard switching flyback converter counterpart.

II. Zcs-Pwm Flyback Converter

The block diagram for the converter is shown in fig.1. Here the first block represents the input dc power supply which is 100V. The supply is provided to the flyback converter shown in fig.2. The control to the converter is provided through the control circuit. The converter provides an output dc voltage of 12V.

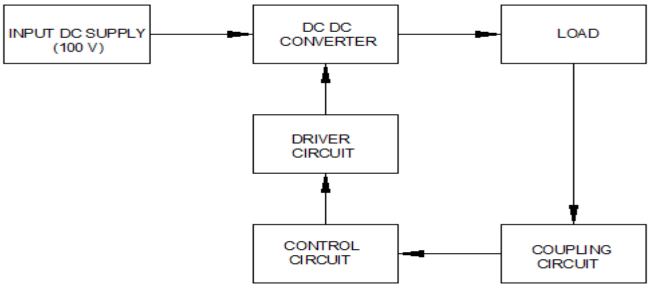

Fig. 1 Block diagram for zcs-pwm converter

A. Circuit Description

The circuit for the converter is shown in fig. 2. The circuit consists of two sections. The first part is the conventional flyback converter, which consists of an isolated transformer, switch Sm, diode D_1 and the output filter C_0. The second part consists of an auxiliary circuit to provide ZCS on the switch Sm. This consists of auxiliary diodes D_2, D_3, the resonant inductor Lr, the resonant capacitor Cr and the auxiliary switch Sa.

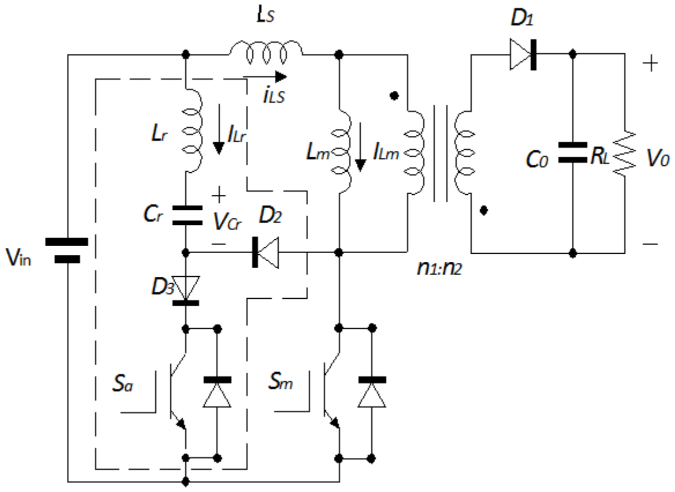

Fig. 2 ZCS-PWM flyback converter

a. Principle of Operation

The operation for the converter system is explained as follows:

When the main switch S_m is on, L_m and L_s are charged by the input voltage source and the converter operation is same as that of a conventional hard-switched flyback converter. The auxiliary switch S_a is turned on just before S_m is turned off resulting in resonance between L_r and C_r. The resonant capacitor C_r is discharged by the resonant current in the auxiliary circuit. When the resonant current reaches zero, the diode D_2 seizes conduction and stops the flow of resonant current through S_a. The resonant current now flows through D_1 and charges C_r. When the resonant current through S_m reverses, the antiparallel diode D_m begins to conduct. When the diode D_m seizes conduction, the current through S_m is zero thereby creating a ZCS condition for S_m and S_a. The switches S_m and S_a are turned off during this time period. When the switches are turned off, the resonance between L_s, L_r, and C_r begin, and the resonant current continues to charge C_r. The output rectifier D_1 is forward biased and the magnetizing inductance current is transferred to the load. When the energy stored in L_r and L_s is transferred to C_r, the diode D_1 commutates all of the magnetizing inductance current to the output until S_m is turned on in the next switching cycle.

Advantages

- All the semiconductor devices are turned on softly and turned off with ZCS condition.
- The circulating current flows only through the auxiliary circuit and hence there is no additional current stress on the main switch.
- The auxiliary switch conducts for a very small period of time resulting in reduced conduction losses due to circulating current.
- The auxiliary switch is referenced with respect to the ground making it easier to drive.
- The auxiliary switch is turned off at the same time instant as that of the main switch making the control logic simpler.

Disadvantages

- When both the switches are turned off, the parasitic output capacitance of the main switch, auxiliary switch, auxiliary diode D_{a1}, and the rectifier diode D participate in the resonance of L_l, L_r, and C_r, due to which the voltage stresses across S_p, S_a, D_{a2}, and D are significantly increased.
- Since the voltage across Cr swings from $-4V_I$ to $6V_I$, the stresses of Cr can be very large in high input voltage applications.
- The ZCS-PWM commutation cell needs an additional inductor L_r for the resonance. Also two additional auxiliary diodes are required for proper ZCS operation.

A. *Stages of operation*

Mode 1: [Fig.3(a): $t_0 < t < t_1$*]:* is Before $t = t_0$, both switches S_m and S_a maintain turn-off state. The energy stored in magnetizing inductor *L*m is delivered to output filter capacitor C_o and loaded through the ideal transformer and diode *D*1. This stage started when the main switch S_m turns on with ZCS at $t = t_0$. The leakage inductor L_s charges linearly to output voltage *V*o from zero to I_{Lm}. The stage ends when the current in the leakage inductor *L*s reaches I_{Lm} and diode D_1 turns off with ZCS at $t = t1$. The resonant current *i*Lr(*t*), resonant voltages $V_{Cr(t)}$, and the current $i_{Ls(t)}$ in leakage inductor can be described as

$$i_{Lr}(t) = 0 \quad (1)$$

$$i_{Ls}(t) = (V_{in} + nV_0)(t - t_0) \quad (2)$$

$$V_{Cr}(t) = V_{Cr0} \quad (3)$$

$$\Delta t_1 = I_{Lm} L_s / V_{in} + nV_0 \quad (4)$$

Mode 2 [Fig.3(b): $t_1 < t < t_2$*]:* When the current *i*Ls(*t*) in leakage inductor *L*s reaches *I*Lm and diode *D*1 turns off with ZCS at *t* = *t*1, this stage is started. The magnetizing inductor *L*m and the leakage inductor *L*s are linearly charged by input voltage source *V*in together. This operating behaviour is the same as the conventional PWM flyback dc/dc converter operating at turn-on state. The resonant current *i*Lr(*t*), resonant voltages $V_{Cr(t)}$, and the current $i_{Ls(t)}$ in leakage inductor can be described as

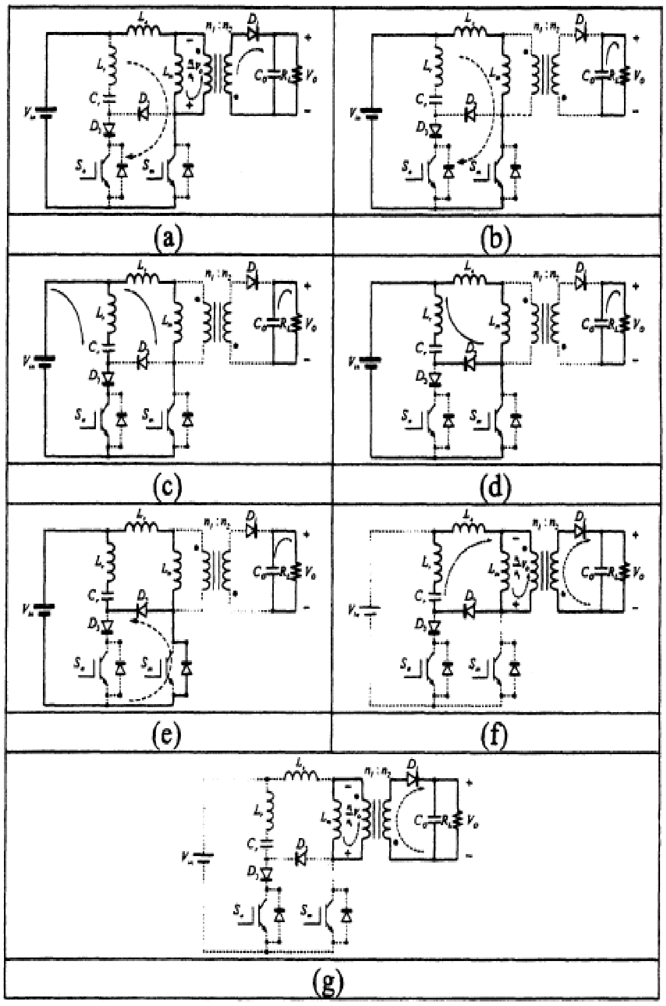

Fig. 3 Seven dynamic equivalent circuits of converter during one switching cycle

$$i_{Lr}(t) = 0 \qquad (5)$$

$$i_{Ls}(t) = I_{Lm} \qquad (6)$$

$$v_{Cr}(t) = V_{Cr0} \qquad (7)$$

$$\Delta t_2 = DT_S - \Delta t_1 \qquad (8)$$

where *D* is the duty ratio and time of the main switch at turn-on state in a conventional PWM flyback dc/dc converter, *T*s = 1/*f*s is the switching period, and *f*s is the switching frequency.

*Mode 3 [Fig.3(c): t*2 < *t* < *t*3*]:* This stage begins when the auxiliary switch *S*a is turned on at $t = t_2$. Because the initial value of resonant current $i_{Lr}(t)$ is zero, ZCS in auxiliary switch *S*a can be achieved. The resonance of resonant inductor *L*r and capacitor *C*r is started by V_{in}, *L*r, *C*r, D_3, and *S*a. The resonant current $i_{Lr}(t)$ increases and then decreases when it reaches peak value. The resonant voltage $v_{Cr}(t)$ also increases. The magnetizing inductor *L*m and the leakage inductor *L*s are continuously charged by input voltage source V_{in} together. This state ends when the resonant current $i_{Lr}(t)$ drops to null again and the resonant voltage has reached its peak value. The
diode D_3 is naturally closed. The resonant current $i_{Lr}(t)$, resonant voltages $v_{Cr}(t)$, and the current $i_{Ls}(t)$ in leakage inductor can be described as

$$i_{Lr}(t)= \sin \omega_r \ (t - t_2) \qquad (9)$$

$$i_{Ls}(t) = I_{Lm} \qquad (10)$$

$$V_{Cr}(t) = Vin + (V_{Cr0} - V_{in})\cos \omega_r (t-t_2) \qquad (11)$$

$$t_3=\pi/\omega r \qquad (12)$$

where $Z_0 = \sqrt{Lr}/\sqrt{Cr}$, $\omega_r = 1/(\sqrt{Lr}\sqrt{Cr})$

Mode 4 [Fig.3(d): $t_3 < t < t_4$*]:* In this stage, the resonant behaviour in stage 3 is maintained, but the resonant route changes following V_{in}, *L*r, *C*r, D_2, and S_m. The resonant voltage $v_{Cr}(t)$ decreases and the resonant current $i_{Lr}(t)$ rises toward its negative peak value. The magnetizing inductor L_m and the leakage inductor L_s are continuously charged by input voltage source V_{in} together. The stage is finished when the resonant current $i_{Lr}(t)$ rises to $-I_{Lm}$ at $t = t_4$. The resonant current $i_{Lr}(t)$, resonant voltages $v_{Cr}(t)$, and the current $i_{Ls}(t)$ in leakage inductor can be described as

$$i_{Lr}(t) = (Vin-VCr_0)/Z_0 \sin \omega_r (t-t_2) \qquad (13)$$

$$i_{Ls}(t) = I_{Lm} \qquad (14)$$

$$v_{Cr}(t) = V_{in} + (V_{Cr0} - V_{in}) \cos \omega_r (t - t_2) \qquad (15)$$

$$\Delta t_5 = (1/\omega r) \sin^{-1} (I_{Lm} Z_0) / (V_{in} - V_{Cr0}) \qquad (16)$$

Mode 5 [Fig.3(e): $t_4 < t < t_5$*]:* At $t = t_4$, the resonant current $i_{Lr}(t)$ rises to $-I_{Lm}$ and its flow path is changed by V_{in}, L_r, C_r, D_2, and the antiparallel diode of *S*m. Thus, no current flows through the main switch *S*m. Furthermore, because the diode D_3 is naturally closed at *t* = *t*3, no current also flows through the auxiliary switch S_a. It is the best time to turn off the switches S_m and S_a under ZCS. The switches S_m and S_a are simultaneously turned off at ZCS at $t = t_4$ and this stage is started. In this stage, the resonant operation in stage 3 is continuously maintained, while the resonant voltage $v_{Cr}(t)$ continuously drops. The resonant current $i_{Lr}(t)$ rises toward its negative peak value and then decreases. The magnetizing inductor *L*m and the leakage inductor *L*s are continuously charged by input voltage source V_{in} together. When the resonant current $i_{Lr}(t)$ drops to $-I_{Lm}$ again, the antiparallel diode of *S*m is naturally closed and this stage is finished. The resonant current *i*Lr(*t*), resonant voltages *v*Cr(*t*), and the current *i*Ls(*t*) in leakage inductor can be described as

$$i_{Lr}(t) = (Vin\text{-}VCr_0)/Z_0 \sin \omega_r (t - t_2) \quad (17)$$

$$i_{Ls}(t) = I_{Lm} \quad (18)$$

$$v_{Cr}(t) = V_{in} + (V_{Cr0} - V_{in}) \cos \omega_r (t - t_2) \quad (19)$$

$$\Delta t_5 = \pi/\omega_1 \text{-} \Delta t_4 \quad (20)$$

*Mode 6 [Fig.3(f): t*5 < *t* < *t*6*]:* During this stage, the antiparallel diode of S_m is naturally closed and the diode *D*1 is turned on with ZCS. The energy stored in magnetizing inductor L_m begins to load through D_1 and the voltage across the primary winding is fixed in −*nV*o. Thus, another resonant route is formed by *C*r, *L*r, *L*s, *nV*o, and D_2. The resonant voltage $v_{Cr}(t)$ continuously decreases. The resonant current $i_{Lr}(t)$ rises toward zero value and the current $i_{Ls}(t)$ in the leakage inductor drops toward zero value. This stage ends when the energies stored in the resonant inductor *L*r and the leakage inductor *L*s are completely transferred to the resonant capacitor *C*r. The resonant current *i*Lr(*t*), resonant voltages *v*Cr(*t*), and the current *i*Ls(*t*) in leakage inductor can be described as

$$i_{Lr}(t) = -I_{Lm}\cos\omega_r 1/(\sqrt{}(1+n_L))(t-t_5) - (nV_0+VCr(t_5))/(Z_0/(\sqrt{}(1+n_L))\sin\omega_r 1/(\sqrt{}(1+n_L))(t\text{-}t_5) \quad (21)$$

$$i_{Ls}(t) = \text{-}i_{Lr}(t) \quad (22)$$

$$V_{Cr}(t) = (nV_0 - V_{Cr}(t_5))\cos\ \omega_r\ 1/(\sqrt{}(1+n_L)(t\text{-}t_5)\text{-} Z_0/(\sqrt{}(1+n_L)\ I_{Lm}\sin\ {}_r 1/(\sqrt{}(1+n_L)\ (t\text{-}t_5)\text{-}nV_0 \quad (23)$$

$$\Delta t_6 = (\sqrt{}(1+nL))/(\omega r)\sin^{-1}[I_{Lm}/\sqrt{}[(\text{-}I_{Lm})\hat{}2+ [(nV_0+V_{Cr}(t5))/Z_0\sqrt{}(1+n_L)]\hat{}2] \quad (24)$$

$$i_{Lr}(t) = 0 \quad (25)$$

$$i_{Ls}(t) = 0 \quad (26)$$

$$V_{Cr}(t) = V_{Cr0} \quad (27)$$

$$\Delta t_7 = (1 - D)Ts - \textstyle\sum t_k \quad \text{where } k=1 \text{ to } 6 \quad (28)$$

Mode 7 [Fig.3(g): $t_6 < t < t_7$*]:* In this stage, the resonant current $i_{Lr}(t)$ and the current $i_{Ls}(t)$ in leakage inductor *L*s is equal to zero, and the diode D_2 is naturally turned off with ZCS. The energy stored in magnetizing inductor L_m is continuously loaded through D_1. This operating behaviour is the same as the conventional PWM flyback dc/dc converter operating at turnoff state. The resonant current $i_{Lr}(t)$, resonant voltages $V_{Cr}(t)$, and the current $i_{Ls}(t)$ in leakage inductor can be described as (25) – (28)

After stage 7, the circuit operation returns to the first stage. The resonant voltage *v*Cr(*t*) returns to the initial value V_{Cr0}. Both resonant current *i*Lr(*t*) and *i*Ls(*t*) return to zero.

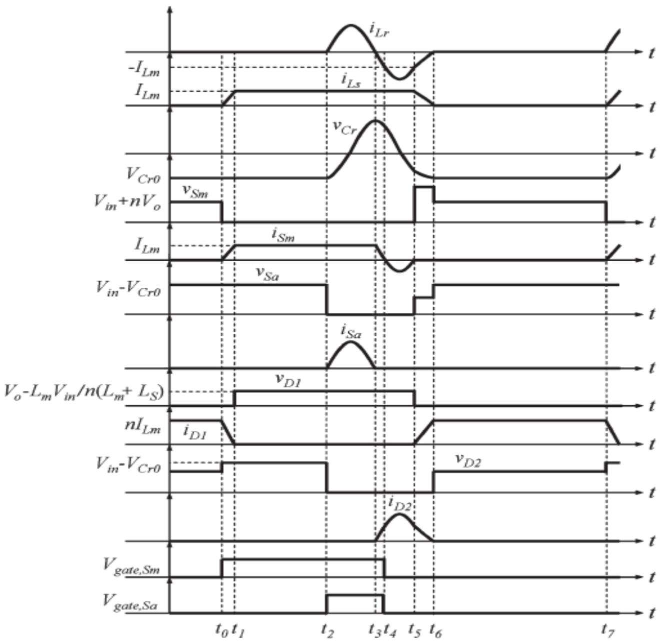

Fig. 4 Ideal waveform of ZCS-PWM flyback converter

III. Experimental Setup

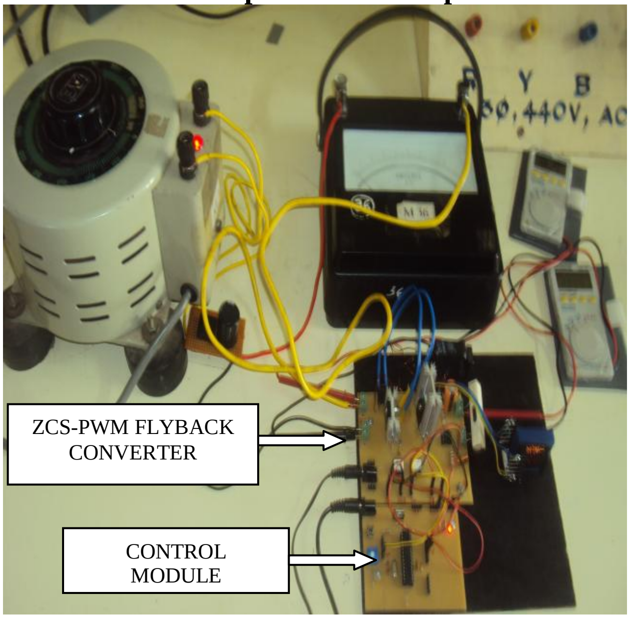

Fig. 5 Experimental setup of zcs-pwm flyback converter

Figure 5 shows the experimental setup of zcs-pwm flyback converter. It consists of an autotransformer associated with a rectifier module to provide an input voltage of 0-100V dc.The control module is provided with 12V dc supply. A 15V dc supply is provided to the converter module for the optocouplers. The output voltage is measured and is obtained as 12V dc. The specifications are:

1) Input Voltage → 100V dc
2) Output Voltage → 12V dc
3) Switching Frequency → 80kHz

The hardware parameters are:

1)Transformer magnetizing inductor L_m: 800 μH
2) Transformer turns ratio n: 3
3) The resonant parameters: L_r = 20 μH, C_r = 16 nF.
4) Power switches and diodes: S_1, S_2: FGA25N120s, 1N4007
& 1N5822
5) The output capacitor: C_o = 470 μF

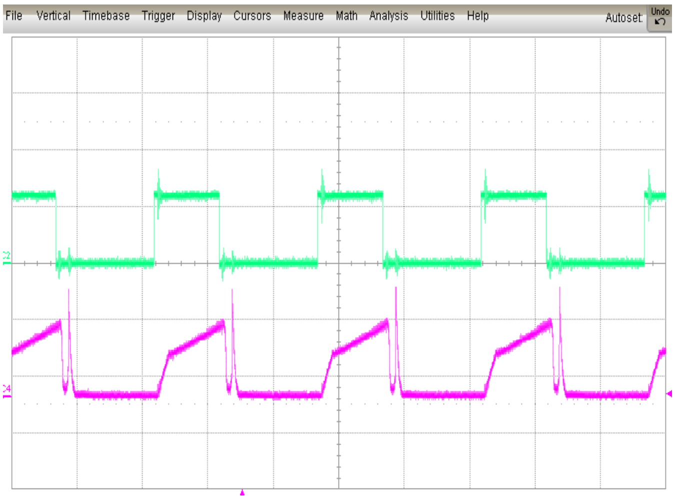

Fig. 6 Zero Current Switching of main switch Sm

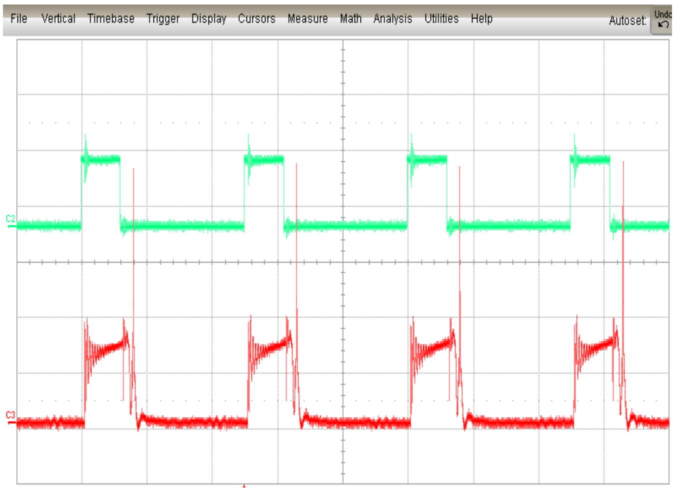

Fig. 7 Zero Current Switching of auxiliary switch Sa

The hardware results shown in Fig.6 and Fig.7 shows the achievement of zero current condition demonstrate that ZCS is achieved at constant frequency for both active switches (*S*m and *S*a). It should be noted that the auxiliary diode *D*1 and the main diode *D*2 were also softly commutated under ZVS. Therefore switching energy losses for the zcs-pwm converter are practically zero. The main switch and diode have no additional current stress compared to the conventional converter.

IV. Conclusion

This paper discusses about a simple and compact configuration of new ZCS-PWM flyback converter. The principle of operation and different modes of operation are analysed. Experimental results in section III shows that ZCS condition is achieved for both the switches. The proposed converter is regulated by the conventional PWM technique at constant frequency.Therefore, the ZCS-PWM flyback dc/dc converter combines the advantages of the PWM and ZCS techniques without additional current stresses compared to the conventional hard-switching method, improving converter performance and maintaining high efficiency.

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