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Design & Implementation of Zero Voltage Switching Buck Converter

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Abstract—
Zero voltage switching (ZVS) buck converter is more preferable over hard switched buck converter for low power, high frequency DC-DC conversion applications. In Zero voltage switching converter, turn on & turn off of a switch occurs at zero voltage that results in lower switching losses. In this converter soft switching is achieved by using resonant components. The optimal values of resonant components are determined by using electric functions derived from circuit configuration. This type of soft switched resonant converter offers very low electromagnetic interference (EMI).This study presents the circuit configuration with least components to realize highly efficient zero voltage switching resonant converter. It's feasibility is confirmed with the developed proto type model and experimental results are verified.
Index Terms-- Resonant converter, Soft-Switching, Zero-Voltage- Switching (ZVS).

I. INTRODUCTION

IN DC-DC converters buck regulation is achieved by turn on the switching device for specified duty cycle. High frequency operation of this converter is preferable to reduce the size of the converter. The high frequency operation results in increased power loss in hard switching converters because switching losses are major contribution in the total converter losses and these switching losses increase with increase in switching frequency. The hard switched converter efficiency is low because considerable amount of power is being lost in terms of switching losses. High frequency operation also increases the severity of switching stress and electromagnetic interference (EMI). All the problems of hard switched converters can be solved by soft switched zero voltage switching circuit configuration. In this circuit configuration, the switching frequency is independent of switching losses. so we can increase switching frequency to very high value.

II. COMPARISONS BETWEEN THE RESONANT CONVERTER AND THE TRADITIONAL PULSE WIDTH MODULATOR (PWM) CONVERTER

In traditional PWM converter, high frequency operation is desired to reduce the volume and weight of the converter. But increase in operating frequency leads to an increase in the switching losses, switching stress and EMI. The snubber circuit is connected in parallel to the switch in conventional solution to reduce the dv/dt surge resulting from the switching off. Switching on buffer circuit is connected in series swith the switch to reduce the di/dt surge resulting from switching on. Although snubber circuits overcome the shortcomings of PWM converters, the efficiency of the whole converter is remains low because switching losses just diverted from switch to snubber circuits in conventional solution. In resonant converter, series and parallel combination of inductor and capacitor create resonant condition. Therefore, the turn on and turn off instants of the switch occurs either at zero voltage or at zero current in resonant condition normally called as soft switching. This soft switching effectively reduces the switching losses, switching stress and EMI.

A. Traditional PWM power converter

Generally transistors are used as the switches of the DC-DC converters. In traditional PWM converters, power transistors such as MOSFET, IGBT are adopted as the switching devices. MOSFET is preferable for low voltage and high current applications where as IGBT is preferable for high voltage applications. The duty cycle of the power switch is controlled to achieve buck/boost topology. During the turn on instant current increases linearly results in switching losses. Although the traditional PWM converter is efficient than conventionally adopted linear power converter, it has some drawbacks. The operating frequency of conventional PWM converter must be raised to high value to minimize the volume and weight of the converter. But increase in switching frequency leads to increases the switching losses and it also increases the severity of switching stress and EMI. So there is a frequency limitation on traditional PWM converter (hard switching converter).

1) Switching Losses:

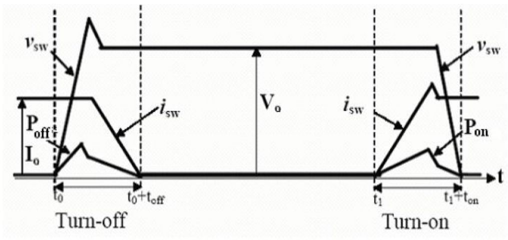

Fig.1.Switching loss in a traditional PWM power converter

In a real semiconductor switch, at switching instant the switch voltage or switch current do not go to zero instantaneously, they exhibit a slope form. There is duration of time during any switching transition (i.e. switch turn-on and turn-off) that results in overlapping of voltage and current waveforms. This overlapped area indicates switching losses. Fig.1 shows the switching losses in the traditional converters. v_{sw} is the voltage drop between collector & emitter of the transistors, and i_{sw} is the current flow from the collector.

B. EMI

The *dv*/*dt* is generated in the voltage waveform at the instance of switching-off, because of the stray inductance during switching-off. The *di*/*dt* is generated at the instance of switching-on, owing to bad reverse recovery characteristics during the switching-on period. These two situations are the source of EMI. EMI also appears increasingly serious with increasing switching frequency.

C. Switching Stress

Fig. 2 displays the switching path in the *V-I* plane in a switched power converter. The switch must withstand the switching stress within a safe operating area (SOA), stress across the switch is due to high voltage and large current appeared in the switch during switching. The performance of the Power semiconductor elements effected if they withstand large switching stress.

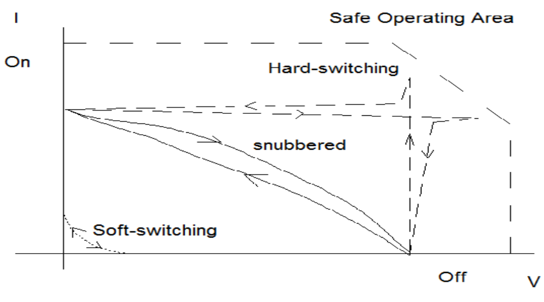

Fig. 2. Typical switching trajectories of power switches.

III. RESONANT POWER CONVERTER

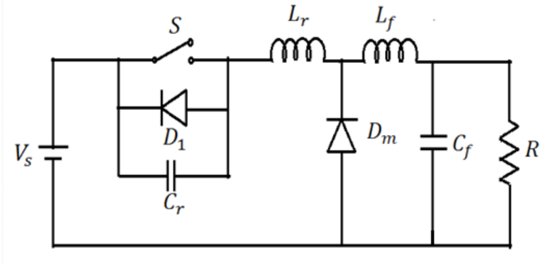

Fig. 3.Circuit diagram of ZVS resonant converter

The resonant power converter utilizes the resonance theory by incorporating a LC resonant circuit as shown in fig. 3 from the conventionally adopted PWM converter[1,2]. The switching-on and switching-off instants of power switch occurs at zero voltage, it will helps to reduce the switching losses, switching stress, *dv*/*dt* and *di*/*dt* surge, and thus EMI. Diode D_1 is connected across the switch with appropriate polarity to ensure turn on instant of power switch at zero voltage. The Inductor L_r is connected in series with power switch S to limit di/dt of the power switch and the capacitor C_r is connected across the switch to limit dv/dt of the power switch. As L_r and C_r forms a series resonant circuit, the oscillation of L_r and C_r initiated by turning off of the power switch. Dm is a freewheeling diode. A low pass filter formed by L_f and C_f is connected at the output terminals to provide constant load current. It also filters the high frequency ripple signal. In ZVS buck converter, soft-switching is applied to the power switch. Because of this special feature ZVS buck converter is suitable for high-frequency conversion applications. The circuit analysis can be simplified by , the choosing large value of output filter inductance so that output filter along with load can be regarded as an ideal dc current source I_0, during a high-frequency resonant cycle. The circuit operation in one switching cycle can be divided into five modes[3,4]. The parameters are defined as follows.

Characteristic impedance, $Z_0 = L_r/C_r$
Resonant angular frequency, $\omega_0 = 1/\sqrt{L_r C_r}$
Resonant frequency, $f_r = \omega_0/2\pi$
Switching period=Ts.

Mode 1:

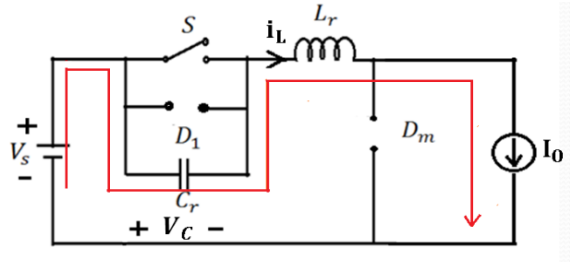

Fig. 4.Equivalent circuit of Mode I

This mode is valid for $0 \leq t \leq t_1$. In this mode switch S and diode D_m are off. Let us assume Capacitor C_r is initially uncharged. During this mode, capacitor C_r charges from zero voltage to a voltage V_S at a constant rate of load current I_0. The capacitor voltage V_C rises linearly and it is given as

$$V_C = I_0.t/C \quad (1)$$

This mode ends at time $t=t_1$.
When

$$V_C(t = t_1) = V_S. \quad (2)$$

We can obtain (3) by substituting (2) into (1)
That is

$$t_1 = \frac{V_S.C}{I_0} \quad (3)$$

Mode 2:

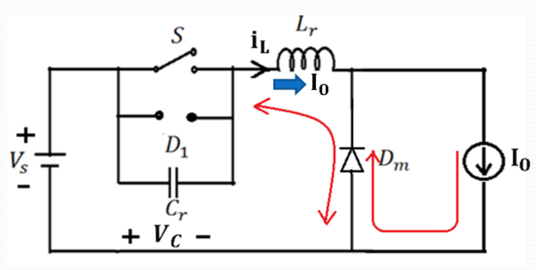

Fig. 5.Equivalent circuit of Mode II

This mode is valid for $0 \leq t \leq t_2$. The switch S is remains off, but diode Dm turns on. The capacitor voltage V_C is given as

$$V_C = V_m \sin \omega_0 t + V_S \quad (4)$$

$$\text{where } V_m = I_0\sqrt{L/C} \quad (5)$$

We can obtain (6) by substituting (5) into (4)
The peak switch voltage is

$$V_t(pk) = V_C(pk) = I_0\sqrt{L/C} + V_S \quad (6)$$

Which occurs

$$\text{at } t = (\pi/2)\sqrt{L/C} \quad (7)$$

The inductor current i_L is given by

$$i_L = I_0 \cos \omega_0 t \quad (8)$$

This mode ends at $t = t_2$

$$V_C(t = t_2) = V_S, \text{ and } \ i_L(t = t_2) = -I_0. \quad (9)$$

$$\text{Therefore,} \quad t_2 = \pi\sqrt{LC} \quad (10)$$

Mode 3:

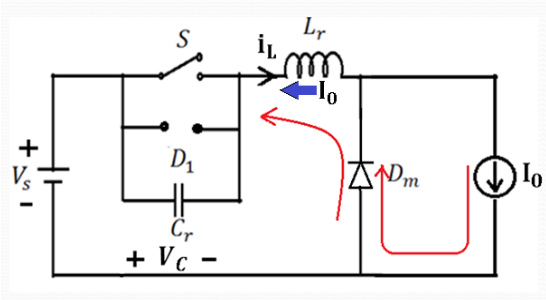

Fig. 6.Equivalent circuit of Mode III.

This mode is valid for $0 \leq t \leq t_3$. The capacitor voltage that falls from V_S to zero is given by

$$V_C = V_S - V_m \sin \omega_0 t \quad (11)$$

The inductor current $i_L$is given by

$$i_L = -I_0 \cos \omega_0 t \quad (12)$$

This mode ends at $t = t_3$

$$V_C(t = t_3) = 0, \text{ and } i_L(t = t_3) = i_{L_3}. \quad (13)$$

$$\text{Thus,} \quad t_3 = \sqrt{L/C}\sin^{-1} x \quad (14)$$

$$\text{Where,} x = \frac{V_S}{V_m} = \frac{V_S}{I_0}\sqrt{L/C} \quad (15)$$

Mode 4:

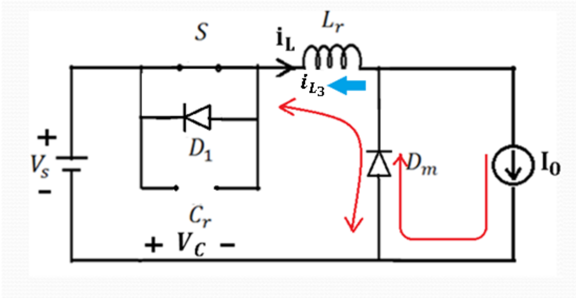

Fig. 7.Equivalent circuit of Mode IV

This mode is valid for $0 \leq t \leq t_4$. Switch S is turned on and diode Dm remains on. The inductor current which rises linearly fromi_{L_3} to I_0 given by

$$i_L = i_{L_3} + (V_S/L)t \quad (16)$$

This mode ends at time $t = t_4$.

$$i_L(t = t_4) = I_0. \quad (17)$$

We can obtain (18) by substituting (17) into (16)

$$t_4 = (I_0 - i_{L_3})(L/V_S) \quad (18)$$

i_{L_3} has a negative value.

Mode 5:

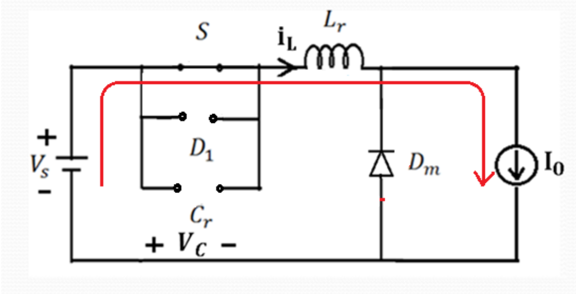

Fig. 8.Equivalent circuit of Mode V.

This mode is valid for $0 \le t \le t_5$.Switch Sis on but Dm is off. In this mode switch carries the load currentI_0. The switch S is turned off at the end of this mode, and the cycle is repeated. i.e.,

$$t_5 = T - (t_1 + t_2 + t_3 + t_4) \quad (19)$$

The waveforms for i_L and V_C are shown in Fig. 9. The peak voltage across the switch is given by

$$V_t(pk) = V_C(pk) = I_0\sqrt{L/C} + V_S$$

The above equation shows that the peak switch voltage $V_t(pk)$ is function of load current I_0.Therefore switch voltage varies with variations in load current that's why we are maintaining load current as constant by using high value of filter inductance. For this reason, ZVS converters are used only for constant-load applications. The switch must be turned on only at zero voltage. Otherwise, the energy stored in C can be dissipated in the switch. To avoid this situation, the anti parallel diode D_1 must conduct before turning on the switch.
The output voltage varies with the switching frequency. Fig. 9 shows key steady-state waveforms of the buck ZVS converter.

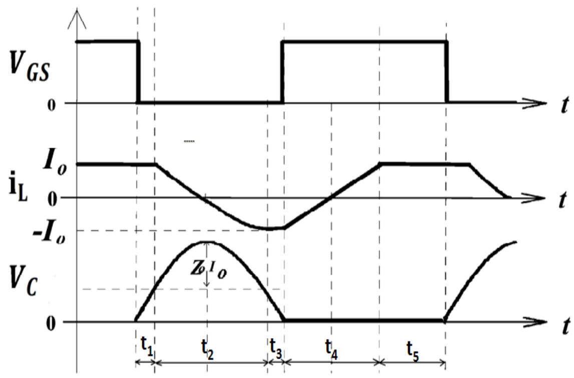

Fig. 9.Steady-state waveforms of the developed zero-voltage-switching resonant converter

IV. DESIGN OF RESONANT ELEMENTS AND SWITCHING FREQUENCY

The condition $Z_0 I_0 > V_S$must hold to ensure that the operation is under zero voltage-switching [5].

$$I_0 \frac{1}{\omega_0 C_r} > V_{in}$$

$$C_r < I_0/(V_{in}\omega_0) \quad (20)$$

Similarly, because of the condition $Z_0 I_0 > V_S$ must hold such that

$$I_0 \omega_0 L_r > V_{in}$$

$$L_r > V_{in}/I_0\omega_0 \quad (21)$$

V. SIMULATION RESULTS

The simulations have been carried out in MATLAB/Simulink. Major circuit parameters are listed in Table I. The values of resonant inductor and resonant capacitor are calculated from design criteria given in the previous section.

TABLE I
CIRCUIT PARAMETERS

Input voltage, V_{in}	24V
Resonant inductor, L_r	200µH
Resonant capacitor, C_r	0.1µF
Switching frequency, f_s	12KHz
Resonant frequency, f_r	50KHz
Output voltage, V_0	12V
Output current, I_0	1A

Simulation of ZVS buck converter is carried out for circuit parameters mentioned in Table I. Fig. 10, shows waveforms of switching signal V_{GS}, resonant voltage V_C and resonant current i_L obtained from MATLAB simulation. Fig. 11 presents the waveforms of input voltage V_S, output voltage V_O and output current I_O.

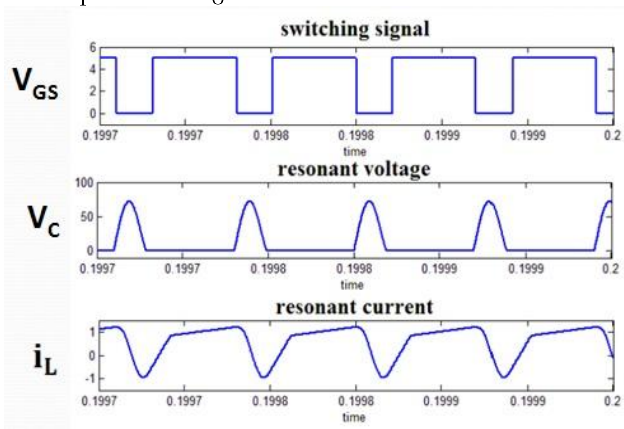

Fig. 10.Waveforms of the switching signal $\mathbf{V_{GS}}$, the resonant voltage $\mathbf{V_C}$, and the resonant current $\mathbf{i_L}$.

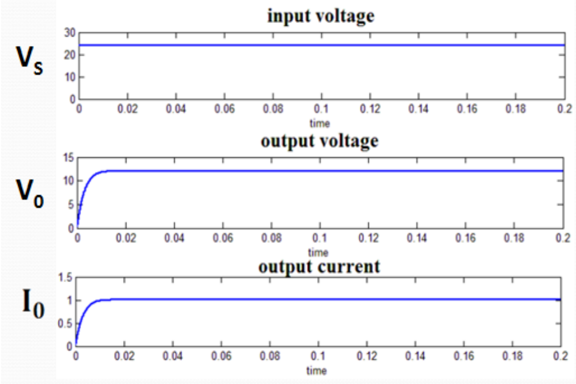

Fig. 11.Waveforms of the input voltage $\mathbf{V_S}$, the output voltage $\mathbf{V_0}$, and the output current$\mathbf{I_0}$

The efficiency of ZVS buck converter can be given as

$$\text{efficiency} = \frac{\text{output power}}{\text{input power}} = \frac{(12)(1)}{(24)(0.54)} = 92.59\%$$

VI. HARDWARE IMPLEMENTATION

A prototype model of the buck converter with zero voltage switching resonant topology was implemented in laboratory to confirm the functional operation. The specifications of different components used in hardware implementation are listed in Table II. While doing implementation switching pulses for MOSFET are obtained by using IC555 timer operated in Astable mode. The circuit connection of IC555 timer operated in Astable mode is shown in Fig. 12.

TABLE II HARDWARE COMPONENTS

COMPONENT NAME	COMPONENT DETAILS
Resonant inductor	200µH
Resonant capacitor	0.1µF
Filter inductor	600µH
Filter capacitor	1000µF
MOSFET	IRF3710
DIODES	IN4007
Timer IC	NE555
Resistors	2kΩ
Capacitor	0.01µF
Variable Resistors	(0-1.6)kΩ

A. Generation Of Switching Signal

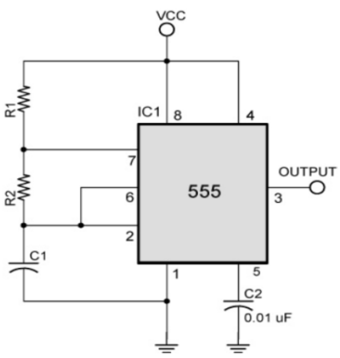

Fig. 12.Astable Operation Circuit

In the Astable Mode, the output gives high and low pulses based on the value of timing resistors R_1, R_2 and timing capacitor C_1.

$$t_1 = 0.693(R_1 + R_2).C_1 \quad (22)$$

$$t_2 = 0.693(R_2).C_1 \quad (23)$$

$$f = 1 / T$$

$$f = 1/ (t_1 + t_2)$$

$$f = \frac{1.44}{(R_1+R_2)C_1} \quad (24)$$

$$\text{Duty Cycle} = \frac{(R_1+R_2)}{(R_1+2R_2)} * 100\% \quad (25)$$

Where:
t_1=the time the pulse is HIGH in sec
t_2=the time the pulse is LOW in sec

Fig. 13.Experimental set up of ZVS buck converter on work bench

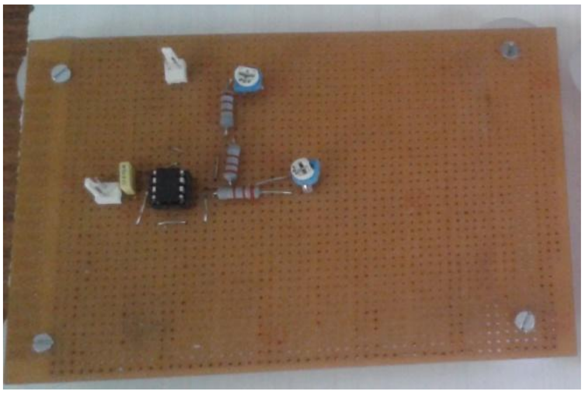

Fig.14. Implementation of Astable circuit by IC555 timer

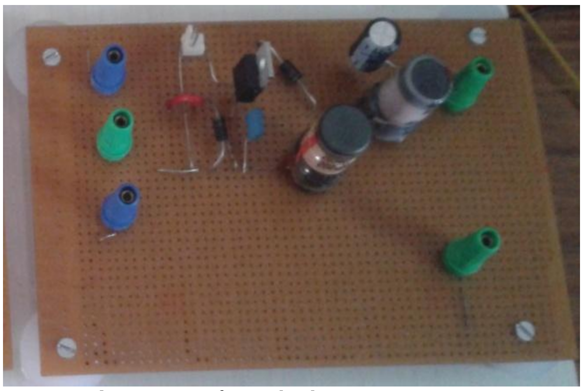

Fig.15. Implementation of ZVS buck converter circuit

Fig.13, displays the experimental set up of ZVS buck converter tested in the laboratory. Fig.14 displays the implementation of Astable mode of operation of IC 555 timer to generate switching signal to the power MOSFET. Fig.15, presents the proto type model of ZVS buck converter.

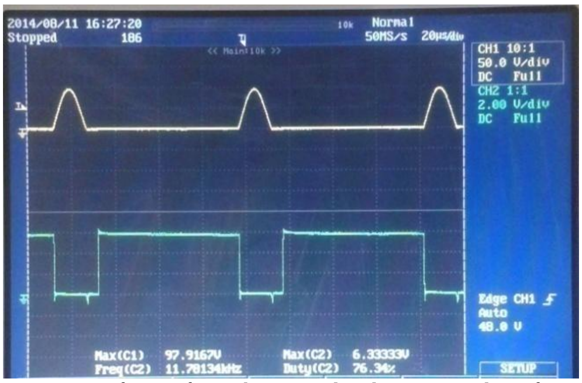

Fig.16 Wave forms of switching signal and resonant voltage from experimental results

Fig.16, presents the waveforms of switching signal and resonant voltage obtained from proto type model. In the figure we can find the amplitude of switching signal is 6.33333 volts and it's duty ratio is 76.34%.The peak voltage of resonant voltage is 97.9167 volts and switching frequency is 11.78 kHz.

Fig.17. Output voltage waveform from experimental results

Fig.17, presents the output voltage waveform obtained from laboratory experimental work. In this figure we can find output voltage as 12.0833 volts and ripple content in the output voltage is 625 mv. The efficiency of ZVS buck converter proto type model is

$$\text{efficiency} = \frac{\text{output power}}{\text{input power}} = \frac{(12.0833)(0.92)}{(24)(0.52)}$$

$$= 89.07\%.$$

VII. CONCLUSION

This study presents the circuit configuration of buck converter with ZVS technology for use in solar battery charging circuits, to demonstrate the effectiveness of developed methodology. The efficiency of ZVS buck converter is in range of 89% to 92%, which is higher than efficiency of traditional PWM buck converter, whose efficiency is in the range of 80% to 85%.Therefore use of ZVS buck converters in solar battery chargers increases the charging efficiency and extends the life of battery charger.

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BIOGRAPHIES

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