EFFICIENCY IMPROVEMENT OF SYNCHRONOUS BUCK CONVERTER BY NEW PASSIVE AUXILIARY CIRCUIT

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Abstract

This paper presents a novel Synchronous buck converter for portable systems. A zero voltage transition is incorporated and designed to operate at high efficiency and lower voltage. The conventional PWM synchronous buck converter is modified by connecting a new passive auxiliary circuit. This auxiliary circuit offers ZVS (zero-voltage switching) for the main switch. Hence this auxiliary circuit enables the circuit with less switching losses and high overall efficiency. Comparative analysis of Synchronous and basic Buck converter is presented using MATLAB/Simulink software and the superiority of auxiliary circuit is proven by the simulation results.

Keywords. Buck Converter, Efficiency, Auxiliary circuit, Synchronous

1. INTRODUCTION

Nowadays, low voltage supplies are gaining their importance in consumer electronics. Due to low conduction losses, synchronous rectifiers are used in most of the LVDC power supplies. A synchronous rectifier [1,11] is an electronic switch that improves power conversion efficiency by offering low conduction losses in a SMPS [6]. Even then, the conversion efficiencies are being decreased due to high input and low output voltages [1,4]. To increase efficiency of the synchronous buck converter, soft-switching techniques [2,10] are adopted, which in turn reduces switching losses. Implementing ZVS [3] offers low conduction losses as its operation is closer to the PWM converters [12]. Just before the instant of turning on of main switch, the auxiliary circuit of the converter [5,16] is activated. It is ceased once the main switch is tuned on [2].

The ratings of the auxiliary circuit components have lower ratings than the other switches, as the auxiliary circuit is made active during a snippet of the switching cycle. This feature offers less amount of switching losses[14,15] than the main switch [4].

SYNCHRONOUS BUCK CONVERTER

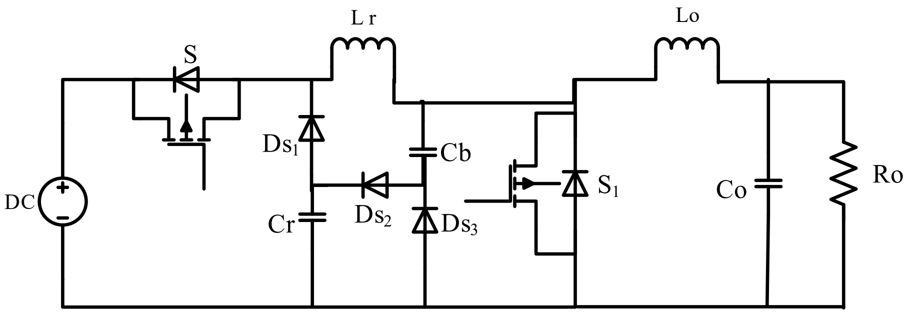


Fig.1. Synchronous Buck Converter with auxiliary circuit

Circuit diagram of a proposed converter with auxiliary [5-6] circuit is shown in Fig. 1. S is considered as main switch and S1 is taken as synchronous switch. The components of auxiliary circuit are resonant capacitor-(C_r), buffer capacitor-(C_b) and resonant inductor-(Lr). D_{S1} D_{S3} and D_{S2} are auxiliary Schottky diodes [12]. The circuit operations over a switching cycle is analysed in eight stages [7,9]. The waveforms of various parameters in all these stages are shown in Fig.2. and the respective equivalent circuits are presented in Fig.3.

Mode 1 (t_0-t_1): When switch S is off and the body diode of Synchronous switch is on, V_{Cb} = 0, i_{D1} = Io, V_{Cr} = 0 Is=0, iLr = 0. At the instant t_0, main switch is on (with zero-current turn-on) [7]. Then the current through resonant inductor rises and current i_{D1} falls simultaneously. The rising and falling of these currents takes place at same rate. This mode ends at t = t_1 as shown in fig.2. The body diode D_1 gets turned off due to the presence of resonant and buffer capacitors. In this state,

$$i_s = i_{Lr} = \frac{V_i}{L_r} X\,(t - t_0) \;\ldots\ldots\ldots..(1)$$

$$i_{D1} = I_0 - I_{Lr} = -\frac{V_i}{L_r}(t - t_0) + I_0 \ldots\ldots(2) \text{ and } \; t_{01} = \frac{L_r}{V_i} I_0 \;\ldots\ldots(3)$$

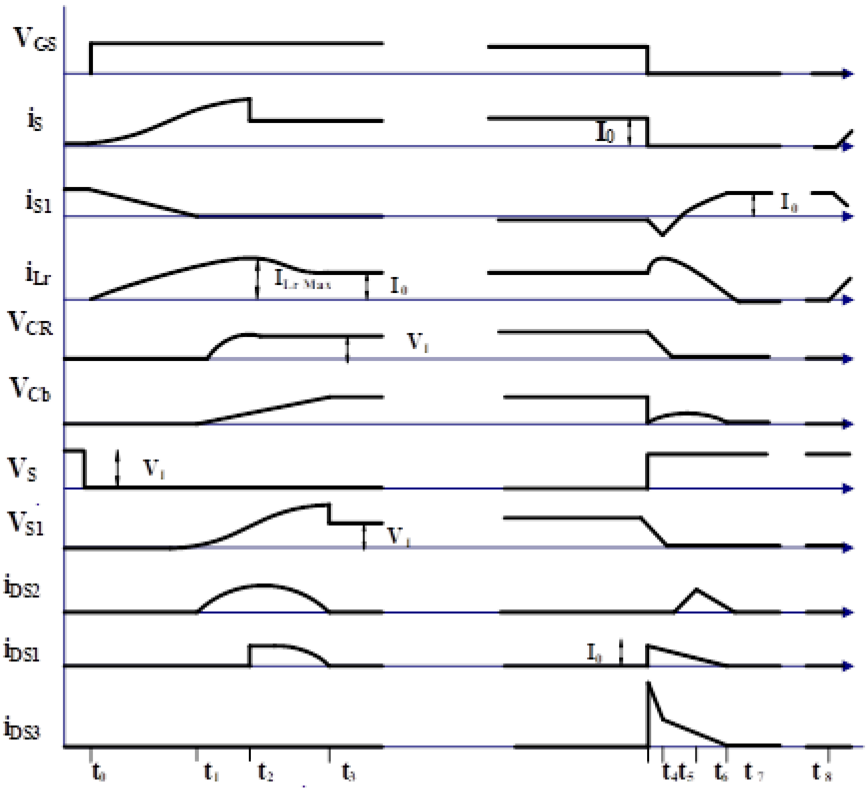


Fig.2. Waveforms of the proposed converter

Mode 2 (t_1-t_2): Diode D_{S2} starts conducting at the instant t_1. Here Voltage across resonant and buffer capacitors is zero. The resonant capacitor and resonant inductor along with buffer capacitor are responsible for the occurrence of resonance. At the end of this stage, the capacitor Cr charges to the supply voltage V_i and makes the diode D_{s1} to conduct

$$i_{Lr}(t-t_1) = \frac{V_i}{Z_1}[\sin\omega_1(t-t_1) + I_0] \quad ....(4)$$

$$v_{cr}(t-t_1) = \frac{C_0}{C_r}\left[-V_i \cos w1(t-t_1) + V_i\right] \quad ....(5)$$

$$v_{cb}(t-t_1) = \frac{C_0}{C_b}\left[-V_i \cos w_1(t-t_1) + V_i\right] \quad ......(6)$$

$$C_0 = \frac{C_r.C_b}{C_r+C_b} \;, ... (7) \qquad \omega_1 = \frac{1}{\sqrt{L_r C_e}} ....(8\,) \quad Z_1 = \sqrt{\frac{L_r}{C_e}} ....(9)$$

$$t_{12} = \frac{1}{w_1}\sin^{-1}\left(\frac{C_0}{C_b} - 1\right) ....(10)$$

Mode 3 (t_2-t_3): When $t = t_2$, $v_{cr} = V_{Cr\max} = V_i$, $v_{cb} = V_{Cb1}$, $i_s = I_0, i_{Lr} = i_{Lr\max}$.

When D_{S1} turns is turned on, resonance is initiated by buffer capacitor and resonance inductor. This mode ends when $i_{Lr} = I_0$ and $VC_b = V_{cbm}$. Both diodes D_{S1} and D_{S2} are turned off under ZCS due to resonance inductor.

$$i_{Lr}(t-t_2) = (i_{Lr\max} - I_0)\cos w_2(t-t_2) - \frac{V_{Cb1}}{Z_2}\sin w_2(t-t_2) + I_0 \quad \ldots\ldots\ (11)$$

$$v_{cb}(t-t_2) = (I_{Lr\max} - I_0)Z_2 \sin w_2(t-t_2) + V_{Cb1}\cos w_2(t-t_2) \quad \ldots\ldots(12)$$

The time interval of this stage can be found as follows:

$$t_{23} = \frac{1}{w_2}\tan^{-1}\left(\frac{I_{Lr\max} - I_0}{V_{Cb1}}\right) \quad \ldots\ldots\ (13)$$

Where

$$w_2 = \frac{1}{\sqrt{L_r.C_b}} \quad Z_2 = \sqrt{\frac{L_r}{C_b}}$$

Mode 4 (t_3-t_4): In this mode, the load current is carried by S and L_r. Now the circuit operates like PWM buck converter[8,12].

Hence $i_s = I_0 = i_{Lr}$.....(14)

Mode5 (t_4-t_5): in this mode, switch S is turned off under ZVS, and the synchronous switch is turned on under ZCS. As S1 is conducting, the voltage across buffer capacitor becomes zero. Resonance inductor and capacitor initiates resonance [13]. The equations are given below,

$$V_{Cb}(t-t_4) = 0 \quad \ldots\ (15)$$

$$i_{Lr}(t-t_4) = I_0 \cos w_3(t-t_4) - \frac{V_i}{Z_3}\sin w_3(t-t_4) \ldots\ldots\ (16)$$

$$v_{cr}(t-t_4) = I_0 Z_3 \sin w_3(t-t_4) - V_i \cos w_3(t-t_4) \ldots\ldots(17)$$

Where, $w_3 = \frac{1}{\sqrt{L_r.C_r}}$ $Z_3 = \sqrt{\frac{L_r}{C_r}}$ and interval of this period is given as $t_{45} = \frac{1}{w_3}\tan^{-1}\left(\frac{V_i}{I_0 Z_3}\right)$

At the end of this stage, $V_{Cr} = 0$ and D_{S2} turn is turned on under ZVS.

Mode 6 (t_5-t_6): L_r and C_b are responsible for new resonance at this stage

$$v_{cb}(t-t_5) = I_{Lr2} Z_2 \sin w_2(t-t_5) \quad \ldots\ldots\ldots(18)$$

$$i_{Lr}(t-t_5) = I_{Lr2}\cos w_2(t-t_5) \quad \ldots\ldots\ldots\ldots(19)$$

This mode ends when $i_{Lr} = I_0$, therefore

$$t_{56} = \frac{1}{w_2} tan^{-1}\left(\frac{I_0}{i_{Lr2}}\right),\ w_2 = \frac{1}{\sqrt{L_r.C_b}}\ Z_2 = \sqrt{\frac{L_r}{C_b}}$$

Mode 7 (t_6-t_7): At $t = t_6$, i_{Lr} becomes I_0 and S_1 is turned off with Zero current switching. L_r and C_b transfer their stored energy to load. The corresponding equations are,

$$v_{cb}(t-t_6) = \frac{I_0}{C_b}(t-t_6) + V_{Cb2} \quad \text{……….. (20)}$$

$$i_{Lr}(t-t_6) = -\frac{V_0}{L_r}(t-t_6) + I_0 \quad \text{……….(21)}$$

At the ned of this stage, i_{Lr} =0. The total time period with respect to this stage is expressed as

$$t_{67} = \left(\frac{I_0 L_r}{V_0}\right) \quad \text{………. (22)}$$

Mode 8 (t_7-t_8): Now body diode of switch S_1 provides path for load current. As long as the switch S is not turned on, the converter operates as a basic PWM buck converter[13] until the switch S is turned on in the next switching cycle. In this mode,

$$i_{s1} = I_0$$

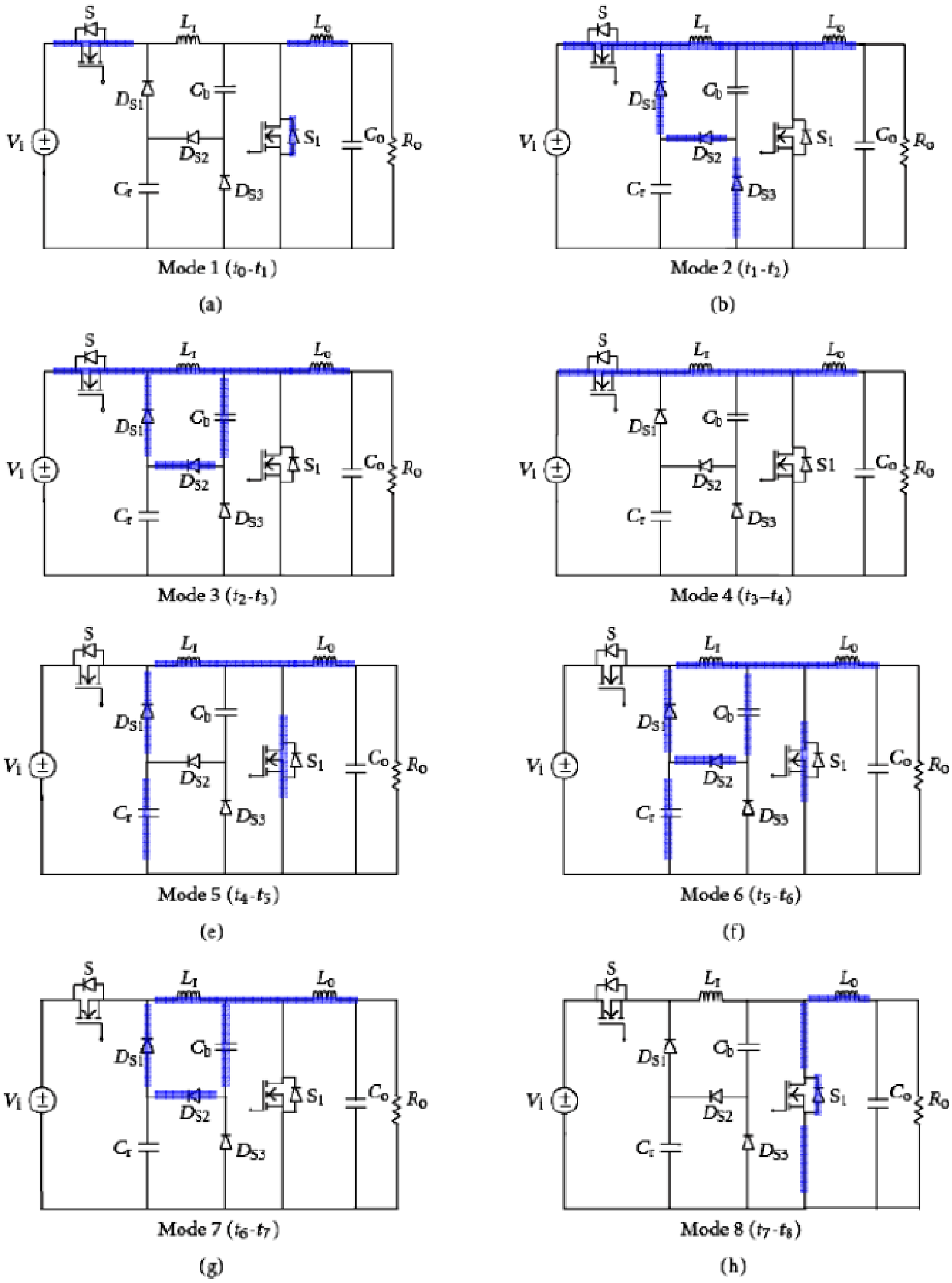


Fig. 3. Modes of Operation

2. SIMULATION RESULTS

Simulink models of simple Buck converter and modified Synchronous buck converter are developed and simulation results are presented. And comparison table is also given , which shows that the synchronous buck converter has 13.1% more efficiency than basic converter. In both the cases Input voltage of 12 V is taken with resistive load.

2.1. Simulated circuit of basic buck converter

The simulated circuit of buck converter with resistive load is shown in fig.4. The output current and voltage of the basic converter are shown in fig. 5a) and b) respectively. For an input voltage of 12V, load current of 0.4A and output voltage of 4.3 V is obtained. The duty ratio is 0.358 in this case.

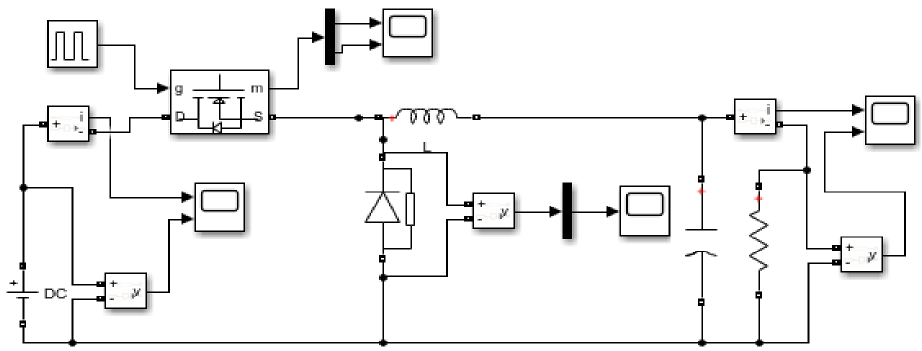


Fig.4. Simulated circuit of basic buck converter

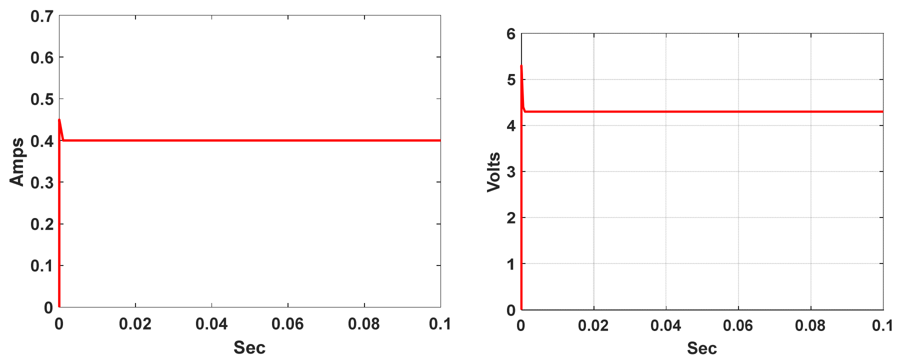


Fig. 5. a) Basic buck converter output current b) Basic buck converter output voltage

2.2. Simulation Results of proposed Converter

SIMULINK Model of the Synchronous buck converter shown in fig.1. is developed and the results are presented. Fig.6. a) and b) gives the output voltage and currents of the converter for an input voltage of 12V and 1A. A current of 11 A and voltage of 3.3V is obtained. The steady state values are achieved at 0.1 sec.

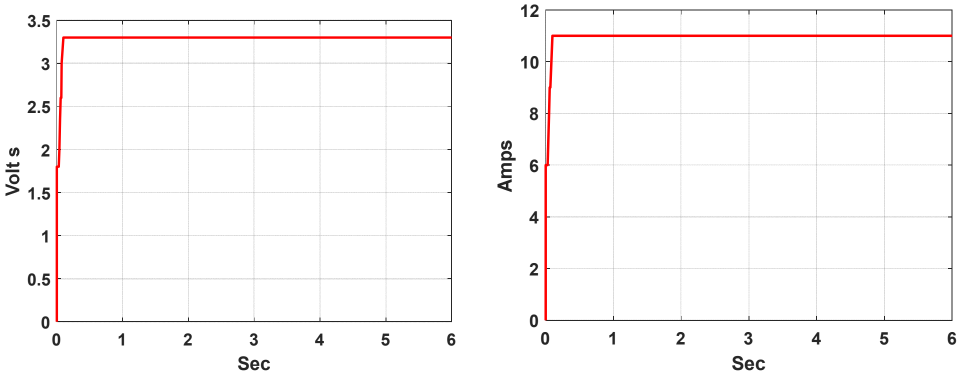


Fig. 6. a) Output Voltage b) Output Current

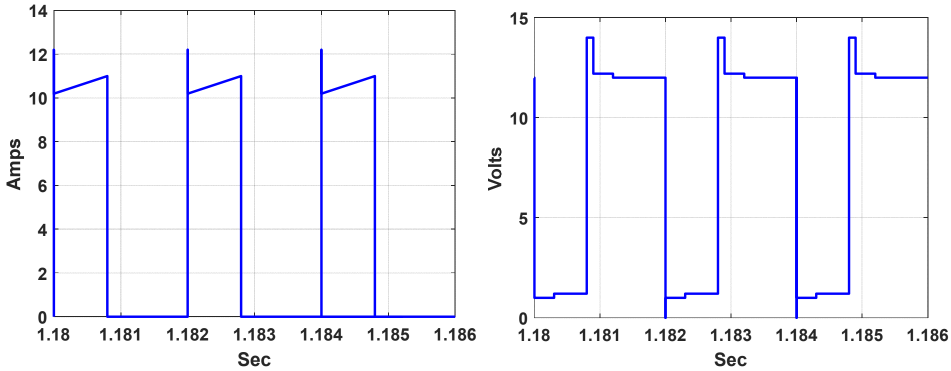


Fig. 7. a) Current though main switch b) Voltage across main switch

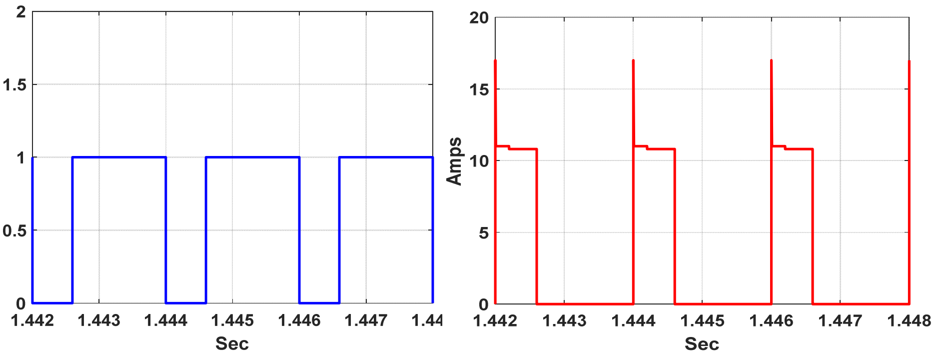
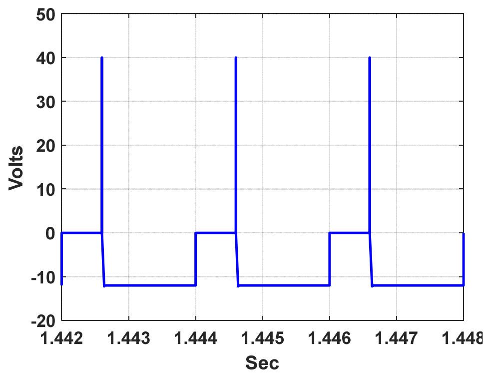


Fig. 8. a) Triggering Pulses for MOSFET Switch b) Current through synchronous switch



c) Voltage across synchronous switch

In fig.8a), the triggering pulses for the MOSFET are shown. Currents and Voltages across the main switch S are shown in fig.7a) and b) respectively. When the switch S is turned on at a time of 1.18sec, current passing through it is 10 A and reaches a maximum value of 11A. When switch S is tuned off, current suddenly falls to "0" and a voltage spikes to a value of 14 and later reaches constant value of 12. Similarly, the current and the voltage of synchronous switch are shown in fig.8.b) and c) respectively. The voltage across the synchronous switch is -12V and during transition the voltage spikes to 40V and the current is 11A.

2.3. *Comparative Analysis*

TABLE I

Type of Converter	**Input Voltage and Currents**		**Output Voltages and Currents**		**Main Switch Voltages and Currents**		**Synchronous switch Voltages and Currents**	
	Volts	**Amps**	**Volts**	**Amps**	**Volts**	**Amps**	**Volts**	**Amps**
Basic Buck Converter	12	1	4.3	0.4	12	1	-	-
Synchronous Buck Converter	12	11	3.3	11	12	10.5	12	10.5

The above comparison table shows that the proposed converter has better efficiency compared to the Basic Buck converter[8], which is 13.1% more.

3. Conclusion

This paper proposed a synchronous buck converter, which has an auxiliary circuit which is befitted for low voltage systems. As both ZCS and ZVS are implemented for switching of main and synchronous switches, switching losses are decreased considerably. The proposed converter is proven efficient when compared to conventional converter. And also stresses on the devices are avoided due to the soft switching implementation.

4. References

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