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Design and Analysis of Zero Current Switching Based DC to DC Buck Converter

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To make the converter size compact, it is to be operated at higher switching frequencies in order of Kilo's and Mega hertz's. The operation of the converter at these higher switching frequencies carrying the entire load current during turn on and turn off instants of the switch, increases the switching losses and is subjected to large amounts of di/dt and voltage stresses. Thus the design and analysis of a high efficient Zero Current Switching (ZCS) based DC to DC buck converter is presented in this paper. The converter uses the ZCS technique with the concept of resonant switch, which is a combination of semiconductor device and LC network, and makes the Switch to turn on and turn off at zero current instant. This reduces the switching losses and improves the life time of the switch. The simulation results in MATLAB/SIMULINK shows the performance of the ZCS based DC to DC Buck converter superior to the normal Buck converter.

Keywords: Resonant switch, Buck converter, Zero Current Switching

1. Introduction

To accommodate the ever increasing requirements for smaller size, lighter weight, and higher efficiency power supplies, switched mode power conversion technologies have evolved from basic pulse width modulated (PWM) converters to resonant converters, quasi – resonant converters (QRCs), multi resonant converters (MRCs), and most recently to soft switching pwm converters. Due to circuit parasitic elements and hard switching condition, operation of PWM converter involves high switching losses, switching stress, and switching noises. These are the major factors that restrict any converters to operate at a higher frequency for size/weight reduction and performance improvement. The switching losses are mainly caused by abrupt discharging of the energy stored in the parasitic capacitance of the semi conductor devices. The proposed ZCS converter turns on and off at zero current values, so that switching losses can be eliminated. The concept incorporates resonant tanks in the converters to create oscillatory (usually sinusoidal) voltage and/or current waveforms so that zero voltage switching (ZVS) or zero current switching conditions can be created for the power switches and the converters are known as soft switched converters[2]. The reduction of switching loss and the continual improvement of power switches allow the switching frequency of the resonant converters to reach hundreds of kilo-Hertz (typically 100 kHz to 600 kHz). Consequently, magnetic size can be reduced and the power density of the converters increased.

Soft-switched converters have switching waveforms similar to those of conventional PWM converters except that the rising and falling edges of the waveforms are 'smoothed' with no transient spikes. Resonance is allowed to occur just before and during the turn-on and turn-off processes respectively, so as

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to create ZVS and ZCS conditions. Soft-switching converters also provide an effective solution to suppress EMI and have been applied to DC-DC, AC-DC and DC-AC converters.

2. Buck Converter

2.1 operation of Buck Converter

In a Buck Converter, the average output voltage V_0 is less than input voltage V_s hence the name "Buck". The circuit diagram of a buck converter using MOSFET as a switch (S) is shown in Fig.2.1. The circuit operation can be divided into two modes[1]. The operation of Mode1 is with switch in ON state. The input current flows through the filter inductor (L), filter Capacitor (C), and load resistor (R) as shown in Fig.2.2.

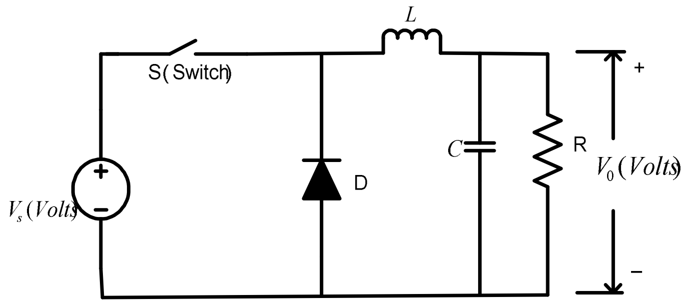


Fig.2.1Buck Converter

The operation of Mode 2 is with switch (S) in OFF state. The diode (D) acts as a freewheeling diode and conducts due to the energy stored in the inductor in ON state, and inductor current continuous to flow through L, C, load and diode D as shown in the Fig.2.3. The inductor current falls until switch is on again in the next cycle. Fig.2.4 shows the output voltage model waveform of the buck converter representing the on period Ton and off period T_{off} with a total time period T, also the average output voltage (V_0) over the period (T) will be less than the input voltage (V_s).

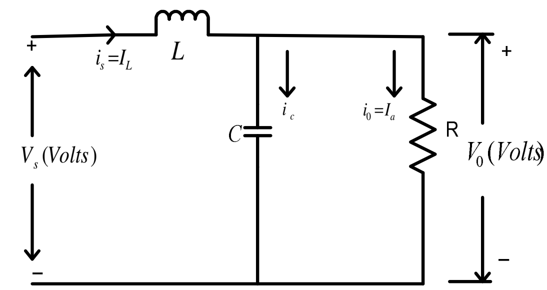


Fig.2.2 Mode 1

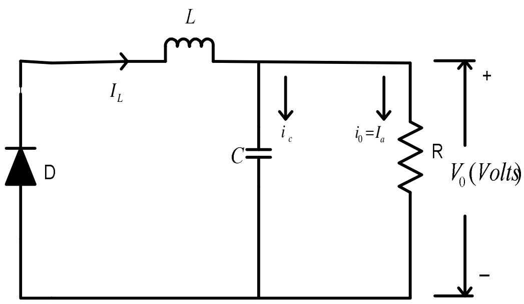


Fig.2.3 Mode 2

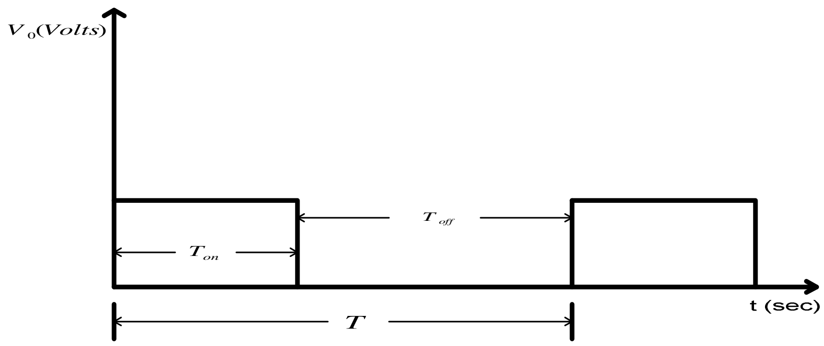


Fig.2.4 model waveform

2.2 ZC Resonant Switch

In a ZC resonant switch, an inductor L_r is connected in series with a power switch S in order to achieve zero-current-switching (ZCS). The resonant switch is said to operate in half-wave mode, when the switch is allowed to resonate in the positive half cycle only. If a diode is connected in anti-parallel with the unidirectional switch, the switch current can flow in both directions. In this case, the resonant switch can operate in full-wave mode. At turn-on, the switch current will rise slowly from zero. It will then oscillate, because of the resonance between L_r and C_r. Finally, the switch can be commutated at the next zero current duration. The objective of this type of switch is to shape the switch current waveform during conduction time in order to create a zero-current condition for the switch to turn off. Thus, the switches of ZCS resonant converters turn ON and OFF at zero current. The resonant circuit that consists of switch S, inductor L_r, and capacitor C_r is shown in Fig.2.5. The inductor Lr is connected in series with power switch S to achieve ZCS. It is classified into two types – (a) **L** type and (b) **M** type [5],[6]. In both the types, the inductor L_r limits the di/dt of the switch current and L_r, C_r constitutes a series resonant circuit.

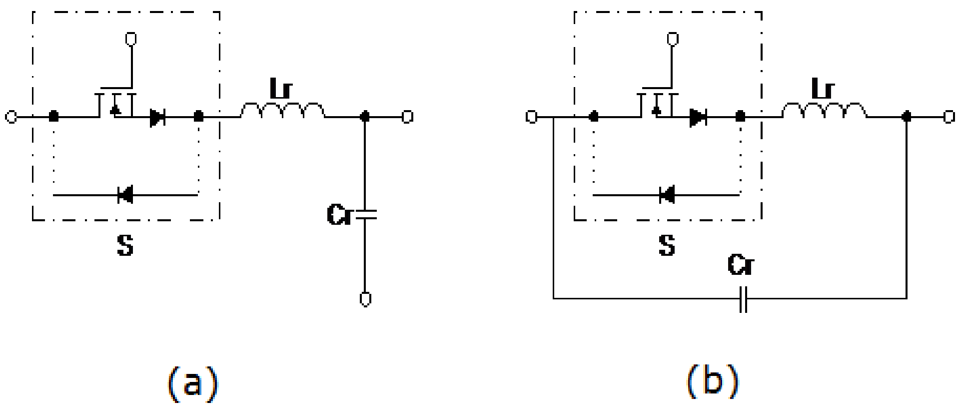


Fig.2.5 ZC Resonant switch.

2.3 Advantages of ZCS over Zero Voltage Switching (ZVS)

ZVS and ZCS are the two conventionally employed soft switching methods. These techniques lead to zero voltage or zero current during switching transition, significantly decrease the switching losses and increase the reliability for the converters. The ZVS technique eliminates capacitive turn-on losses, and decreases the turn-off switching losses by slowing down the voltage rise, thereby lowering the overlap between the switch voltage and the switch current. However, a large external resonant capacitor is needed to lower the turn-off switching loss effectively for ZVS. Conversely, ZCS eliminates the voltage and current overlap by forcing the switch current to zero before the switch voltage rises, making it more effective than ZVS in reducing switching losses, especially for slow switching power devices. Traditional ZCS converters operate with constant on-time control, while the traditional ZVS converters operate with constant off-time control. For high efficiency power conversion, the ZCS topologies are most frequently adopted.

2.4 Operation of ZCS based Buck Converter

Fig 2.6 shows the circuit diagram of ZCS based Buck Converter. The circuit consists of MOSFET switch S, inductor L_r, and capacitance C_r. Inductor L_r is connected in series with the power switch S and Capacitor C_r is connected in parallel with diode D to achieve Zero Current Switching. The inductor L_r limits the di/dt of switch current and L_r and C_r constitute a series resonance circuit[7].

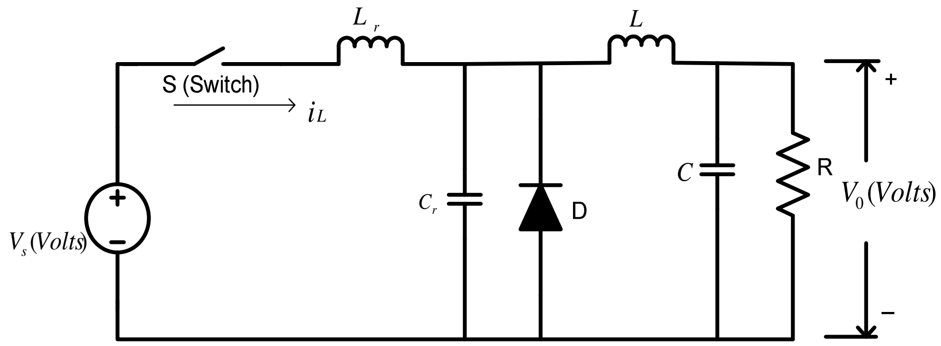


Fig.2.6 ZCS Based Buck converter

Initially both, the capacitor voltage across C_r and inductor current through L_r are assumed to be zero and the load current I_0 freewheels through diode D. Converter operation can be divided into following modes and are explained with the model wave forms of ZCS converter shown in Fig.2.7.

2.4.1 Modes of operation

The ZCS based Buck converter operates in four modes for one switching cycle[4]. Fig.2.7 shows the current through the switch and voltage across the resonant capacitor. The following assumptions are made without loss of generality.

1. All the semiconductor devices used are taken as ideal and operates without any time delay during switching.
2. During the turn-on condition, there is no forward voltage drop and no leakage current under turn-off situation of the switch.
3. The internal resistance is zero for the inductor and capacitor used in the resonant circuit.
4. The filter inductance L and filter capacitance C are much larger than the resonant inductor L_r and resonant capacitor C_r respectively.
5. The filtering circuit formed by the filter inductance L, and the filter capacitance C and the load can be viewed as a constant current I_0, since the cut-off frequency of

the current low-pass filter is far lower than the resonant angular frequency caused by the resonant inductor L_r and resonant capacitor C_r and the simplified circuit is shown in Fig.2.8 (a).

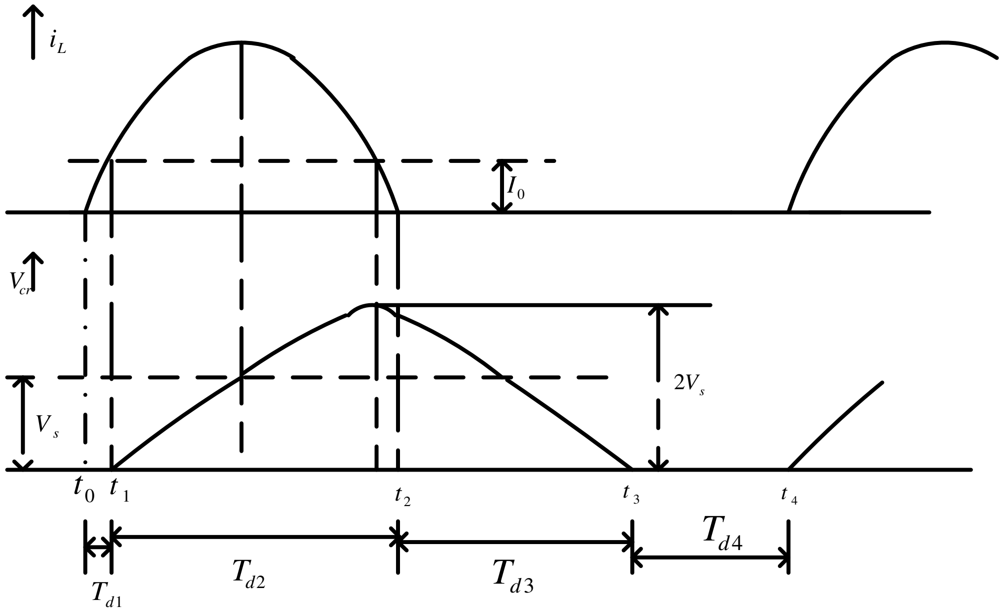
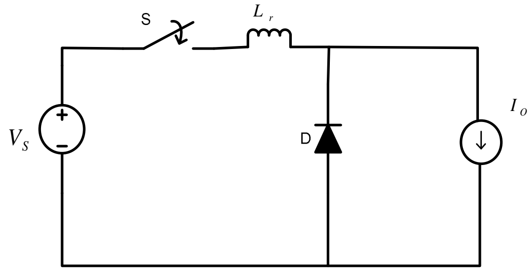


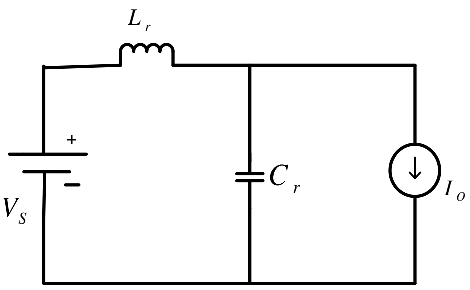
Fig.2.7 Model waveforms of ZCS converter

Mode 1 (t_0 - t_1):

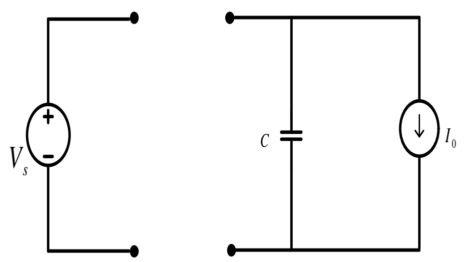
In Mode 1 the switch is turned on at time instant t_0. The equivalent circuit of the converter in Mode 1 is shown in Fig.2.8 (a)



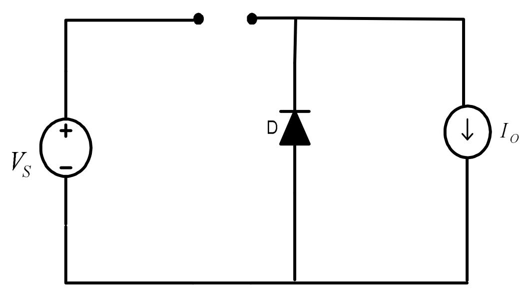
(a) Mode 1



(b) Mode 2



(c) Mode 3



(d) Mode 4

Fig.2.8 Modes of operation of ZCS converter

Before S in conduction, diode D is carrying the output current of I_0 with capacitor voltage V_{C1} clamped at zero. At time t_0, Switch S is turned on, so that current passing through switch S and L_r rises linearly up to t_1 i.e during time interval T_{d1}, as shown in Fig 2.7. Beyond this time t_1, the diode turns off and the voltage clamp across C_r is removed.

Mode 2 (t_1 - t_2):

Fig.2.8 (b) shows the equivalent circuit of the converter in Mode 2. After t_1, diode D is off and i_L is greater than I_0. The difference current i_L- I_0 will pass through the C_r. At time $t_1^{'}$, the switch current i_L peaks and $V_{cr} = V_s$. At time $t_1^{''}$, the switch current drops from its peak value to I_0 and the capacitor voltage reaches to $2V_s$. At time t_2 the switch current eventually drops to zero and cannot reverse through the switch. Thus, the switch is commutated naturally and the gate/drive from the switch should be removed at this point.

Mode 3 (t_2 - t_3):

Fig.2.8 (c) shows the equivalent circuit of the converter in Mode 3. Beyond the time t_2 with the switch off, the capacitor C_r discharges into the output load and the capacitor voltage drops linearly to zero at time t_3.

Mode 4 (t_3 - t_4):

Fig.2.8 (d) shows the equivalent circuit of the converter in Mode 4. From the time instants t_3 to t_4 load current freewheels through diode D. At t_4, again the switch turns on, and the next switching cycle starts at this point.

2.5 Steady State Analysis of ZCS Buck Converter

Before analysing the operation modes of the converter circuit, the circuit parameters are defined as follows

- Resonant inductor L_r in Henry
- Resonant capacitor C_r in Farad
- Switching period T_s in sec.
- Characteristic impedance Z_n in ohm $Z_n = \sqrt{\frac{L_r}{C_r}}$
- Resonant angular frequency ω_0 in rad/sec $\omega_0 = \frac{1}{\sqrt{L_r C_r}}$
- Resonant frequency f_r in Hertz $f_r = \frac{\omega_0}{2\pi}$

The switching cycle is divided in to four stages given the initial conditions of each stage, the state equations [3] of the equivalent circuit models are as follows:

Stage 1: ($t_0 - t_1$)

The voltage across the resonant inductor during the period T_{d1} (i_L less than I_0) is given by

$$V_s = V_{Lr} = L_r\left(\frac{di_L}{dt}\right) \qquad \text{----(1)}$$

and the current $i_L(t)$ from Eq.(1) is given by

$$i_L(t) = \frac{V_s}{L_r} t$$

Initially $I_L(0) = 0$, $I_L(T_{d1})=I_0$ where $T_{d1}=t_1-t_0$, thus

$$V_s = \frac{LI_0}{T_{d1}} \text{ and } T_{d1} = \frac{LI_0}{V_s} \qquad \text{----(2)}$$

Stage 2 : $(t_1 - t_2)$

During this period two currents i_L and I_0 were present and the difference of the currents $(i_L\text{-}I_0)$ will flow through the capacitor C_r and is given by

$$C_r\left(\frac{dV_{cr}}{dt}\right) = i_L(t) - I_0 \qquad \text{----(3)}$$

$$L_r\left(\frac{di_L}{dt}\right) = V_s - V_{cr}(t) \qquad \text{----(4)}$$

By applying Laplace transform

$$I(s) = \left(\frac{V_s}{L_r} * \sqrt{L_r C_r}\right)\left[\frac{\frac{1}{\sqrt{L_r C_r}}}{s^2 + \left(\frac{1}{\sqrt{L_r C_r}}\right)^2}\right]$$

Applying Inverse Laplace transform the current through the capacitor C_r and voltage across the capacitor C_r is

$$i(t) = \frac{V_s}{Z_n} * \sin \omega t \qquad \text{----(5)}$$

$$V_{cr} = \frac{1}{C_r}\int i(t)dt$$

Voltage across capacitor

$$V_{cr} = (-)V_s \cos \omega t + k \qquad \text{----(6)}$$

At t = 0, $\boldsymbol{k}$ = V_s and V_{cr} (t) is given as

$$V_{cr}(t) = V_s(1 - \cos \omega t)$$

Now considering the Eq.(3)

$$C_r \frac{d[V_s(1-\cos \omega t)]}{dt} = i(t) - I_0$$

Where

$$i(t) = \frac{V_s}{Z_n} * \sin \omega t + I_0 \qquad \text{----(7)}$$

Let us consider $\omega T_{d2} = \theta$ where $T_{d2} = t_2 - t_1$
then,

$$T_{d2} = \frac{\theta}{\omega} \qquad \text{----(8)}$$

At T_{d2}, $i(t) = 0$ and Eq.(7) becomes

$$\frac{V_s}{Z_n} * \sin \theta + I_0 = 0$$

$$\theta = \sin^{-1}\left(\frac{-I_0 Z_n}{V_s}\right) \text{ and } \theta \text{ varies from } \pi < \theta < \frac{3\pi}{2}$$

Stage 3: $(t_2 - t_3)$

During this period ($T_{d3}=t_3-t_2$), the voltage across the resonating capacitor discharges to zero and the current is given by

$$-I_0 = i_{cr} = C_r \frac{dV_{cr}}{dt}$$

Now,

$$V_{cr}(t) = \frac{-I_0}{C_r}(t - t_2) + V_{cr}(t_2) \qquad \text{----(9)}$$

$$V_{cr} = \frac{-I_0}{C_r}(t - t_2) + V_s\{1 - \cos[\omega_0(t_2 - t_1)]\} \qquad \text{----(10)}$$

This voltage across the resonant capacitor decreases to zero at time t_3, namely,

$$\frac{I_0}{V_s C_r}(t_3 - t_2) = 1 - \cos[\omega_0(t_2 - t_1)] \qquad \text{----(11a)}$$

$$(t_3 - t_2) = \frac{C_r V_s}{I_0}\{1 - \cos[\omega_0(t_2 - t_1)]\} \qquad \text{----(11b)}$$

The time interval during stage3 can be computed from Eq.(11b)

$$T_{d3} = t_3 - t_2 == \frac{C_r V_s}{I_0}\{1 - \cos[\omega_0(t_2 - t_1)]\} \qquad \text{----(12)}$$

Stage 4 (t_3-t_4)

I_0 remains constant and voltage across the capacitor becomes zero. The duration of this period is $T_{d4} = t_4 - t_3$

Also, $T_{d4} = T_s - T_{d1} - T_{d2} - T_{d3}$ ----(13)

Where T_s= period of switching cycle.

2.6 Design of ZCS Buck Converter

The buck converter with the Zero Current Switching scheme is designed in this section with the formulae described in the steady state analysis of the converter in each stage. The circuit parameters of the ZCS Buck converter are listed in Table I. Here the buck converter reduces the input dc voltage of 20 volts to 14 volts with an improved performance.

1	Input DC Voltage (V_s)	20Volts
2	Resonant inductor (L_r)	2.62µ Henry
3	Resonant capacitor (C_r)	0.52µ Farad
4	Switching frequency(f_s)	105KHz
5	Resonant frequency (f_r)	147KHz
6	Output DC Voltage (V0)	14 Volts
7	Output DC Current (I_0)	7 Amperes
8	Filter inductor (L)	150 µ Henry
9	Filter Capacitor (C)	330 µ Farad
10	Duty ratio (f_s/f_r)	0.71

Table I Circuit parameters of ZCS based Buck converter

3. Simulation results

The performance of the buck converter and ZSC based buck converter are analysed in MATLAB/SIMULINK environment.Fig.3.1 shows the Simulink model of the buck converter with input voltage as 20 Volts and an output bucked voltage of 14 Volts.

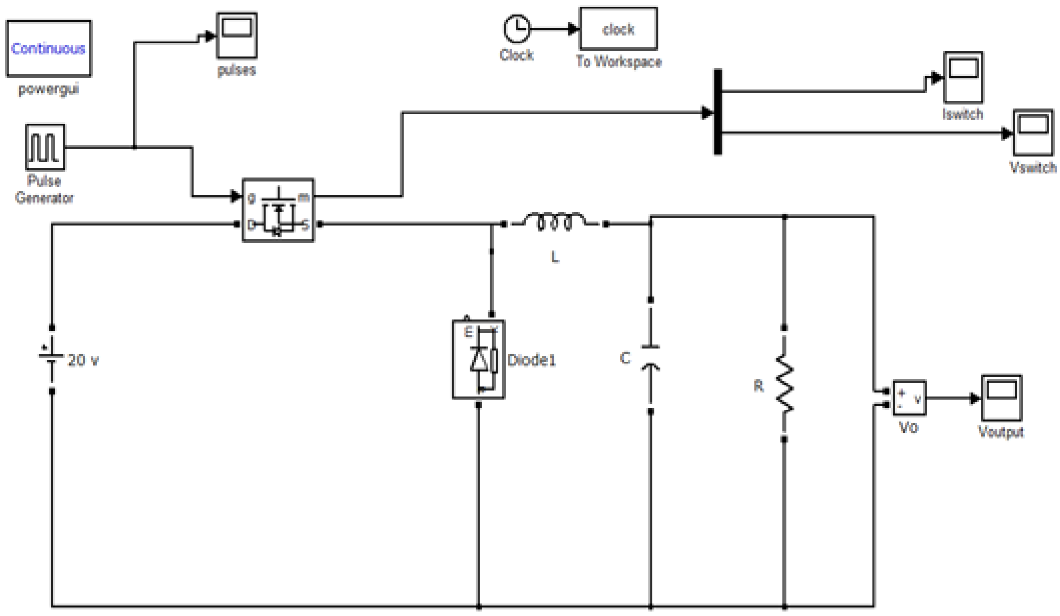


Fig.3.1Simulink model of Buck converter

Fig.3.2 shows the simulink model of the ZCS based buck converter with input voltage as 20 Volts and an output bucked voltage of 14 Volts with the resonant inductor and resonant capacitor values of of 2.62µH and 0.52µF respectively.

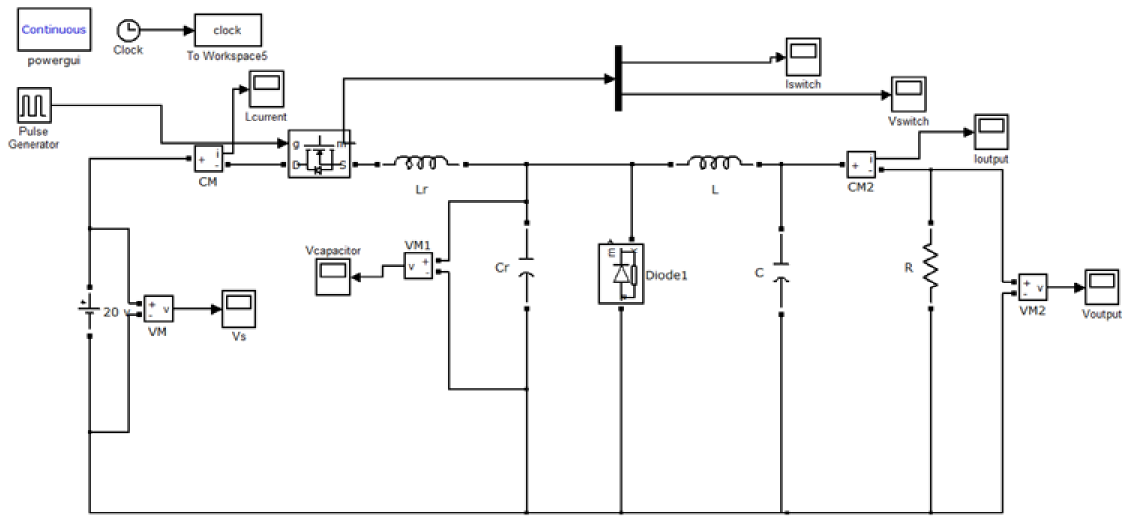
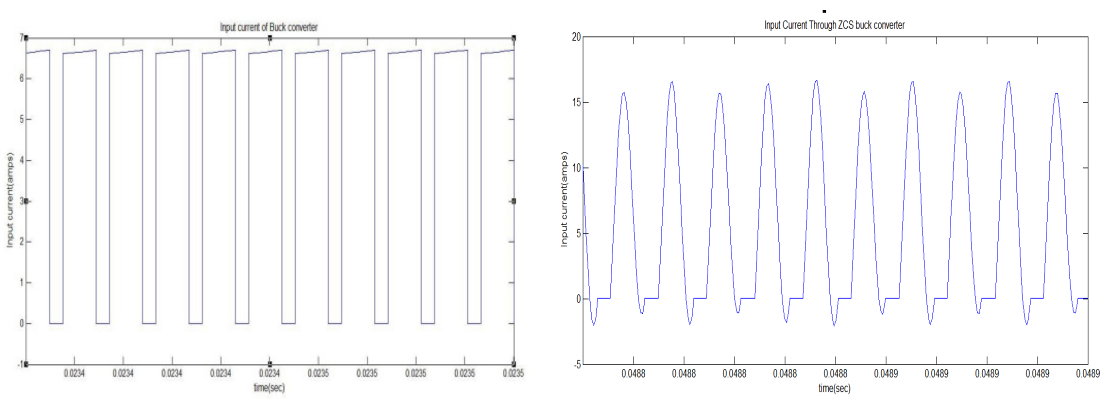


Fig.3.2 Simulink model of ZCS based Buck converter

Fig.3.3 (a) shows the obtained simulated waveform for the supply current of the buck converter and the converter draws an average DC current of 4.57 Amperes from the supply. The supply current is in the form of the pulses synchronized with the gate pulses.

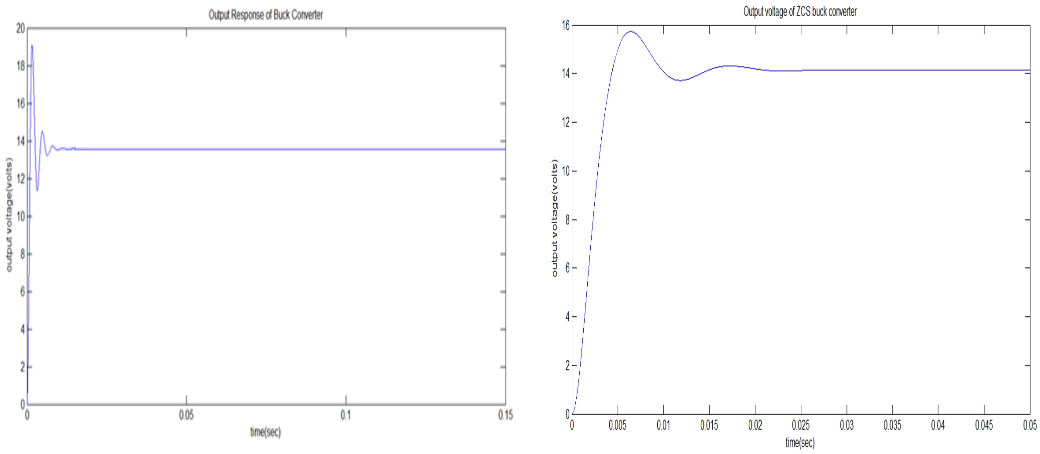


(a) (b)

Fig.3.3 Supply Current of buck and ZCS based Buck converters**.**

Fig.3.3 (b) shows the obtained simulated waveform for the supply current of the ZCS based buck converter and the converter draws an average DC current of 5.57 Amperes from the supply. The supply current is in the form of the pulses synchronized with the gate pulses and also the magnitude of the current becomes zero during the turn on and turn off of the switch instants thus making it as Zero Current Switching.

Fig.3.4 (a) shows the average DC output voltage response of the buck converter and the converter delivers an average DC voltage of 13.6 Volts to the load. The output voltage settles to its steady state value of 13.6 volts at 0.0208 seconds with considerable oscillations

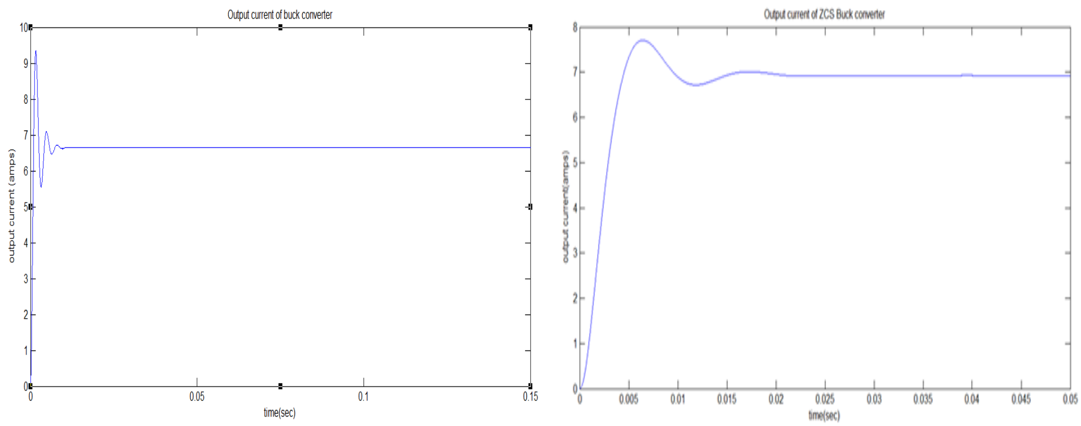


(a) (b)

Fig.3.4 Average output voltage responses of buck and ZCS based Buck converters

Fig.3.4 (b) shows the average DC output voltage response of the ZCS based buck converter and the converter delivers an average DC voltage of 13.8 Volts to the load. The output voltage settles to its steady state value of 13.8Volts at 0.0305 Seconds, with negligible oscillations.

Fig.3.5 (a) shows the average DC output current response of the buck converter and the converter delivers an average DC current of 6.8 Amperes to the load..The output current response settles to its steady state value of 6.8 Amps at 0.013 Seconds

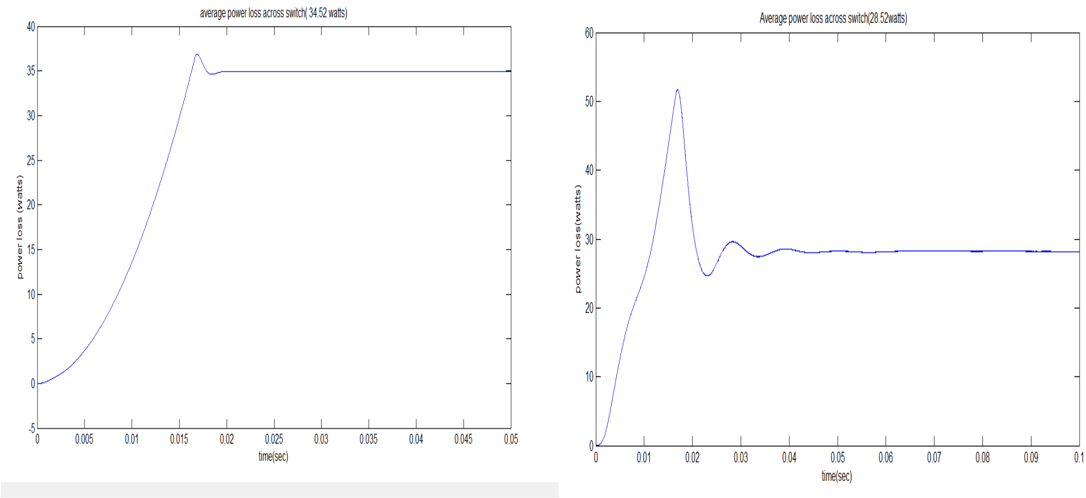


(a) (b)

Fig.3.5 Average output current responses of buck and ZCS based Buck converters

Fig.3.5 (b) shows the average DC output current response of the ZCS based buck converter and the converter delivers an average DC current of 6.9 Amperes to the load..The output current response settles to its steady state value of 6.9 Amps at 0.0158 Seconds

Fig.3.6 (a) shows the average power loss across the MOSFET switch during the operation of the buck converter and the converter dissipates an average power loss of 34.52 Watts across the switch. This power loss comprises of both the switching losses and conduction losses together.



(a) (b)

Fig.3.6 Average power loss across the switch (MOSFET) of buck and ZCS based Buck converters

Fig.3.6 (b) shows the average power loss across the MOSFET switch during the operation of the ZCS based buck converter and the converter dissipates an average power loss of 28.52 Watts across the switch. This power loss comprises of a small amount of the switching losses and major amount of conduction losses. Hence the average power loss has been reduced by 17.38% because of ZCS scheme.

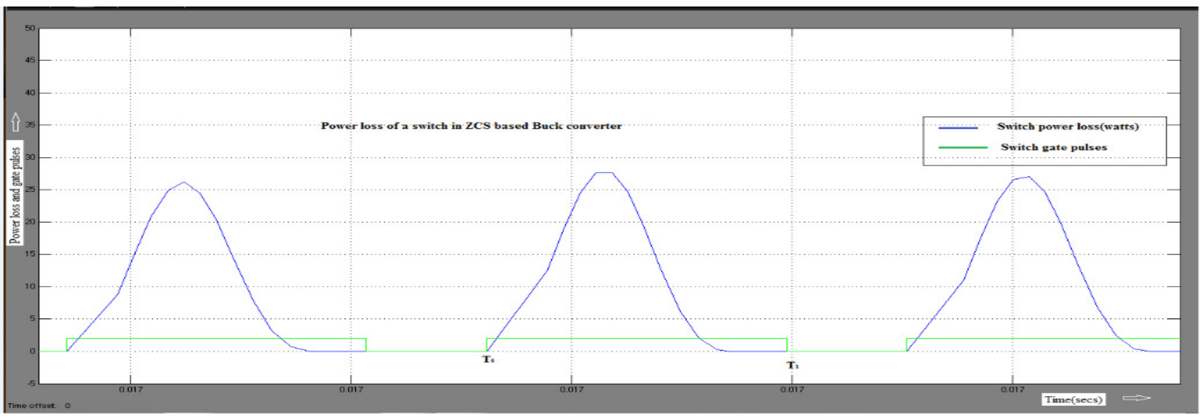


Fig.3.7 Power loss across the switch (MOSFET) of ZCS based buck converter

Fig.3.7 shows the switching power loss and conduction power loss across the MOSFET switch synchronised with the gate pulses during the operation of the ZCS based buck converter and the converter dissipates zero power loss at the instants T_0 and T_1 indicating that the switching losses in the converter as zero. The power losses during the period T_0 to T_1 is considered as the conduction losses. Hence the total average power loss has been reduced as it contains conduction losses only.

Fig.3.8 shows the current through the switch (MOSFET) in synchronization with the gate pulses of the switch in an ZCS based converter. The converter is fully soft switched i.e., at the turn on instant the current in the switch becomes zero as well as at turn off instant also the current becomes zero due to the resonance nature of the elements produced by resonant inductor L_r and resonant capacitor C_r in the converter.

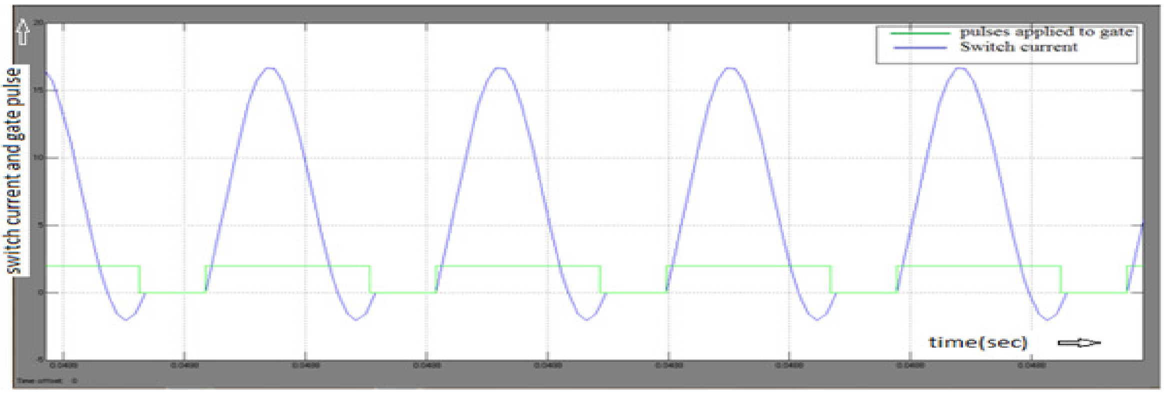


Fig.3.8 switch (MOSFET) current and pulse of ZCS based buck converter

Fig.3.9 shows the voltage response across the resonant capacitor in ZCS buck converter.

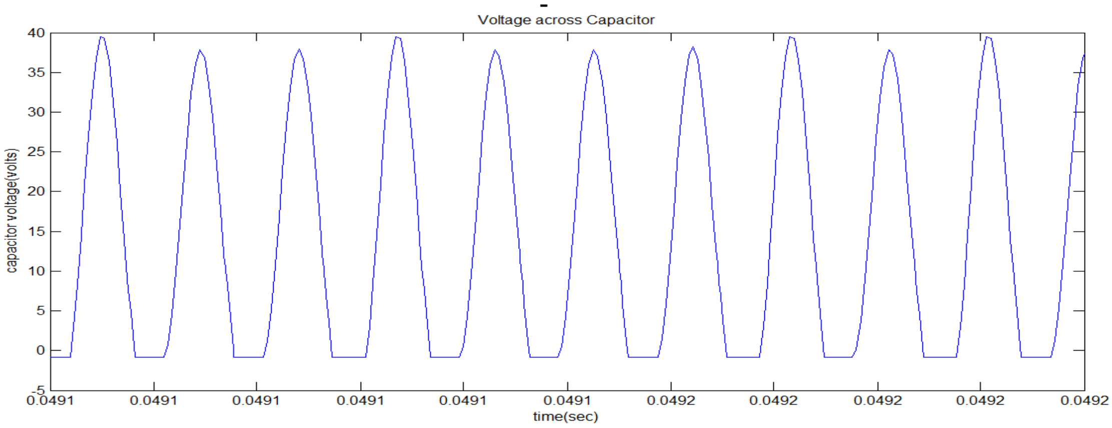


Fig.3.9 Voltage response of the resonant capacitor in ZCS based buck converter

Table II shows the overall performance comparison of the buck and ZCS based buck converters in terms of input voltage, output voltage, and power loss across the switch, input power, output power and efficiency.

S.No	Converter configuratio	Output Voltage	Power loss across the	Input power	Output Power	Efficiency
1.	Buck converter	13.6 V	34.52 W	72.97 W	53.05 W	72.97 %
2.	ZCS based Buck converter	13.8 V	28.72 W	118.2 W	108.8 W	92 %

Table II. Performance comparison of buck converter and ZCS based Buck converter.

From the simulation results the performance of the ZCS buck converter is superior to the buck converter operating at an higher frequency of 105KHz, due to the reduction of the switching losses, there by the total average power loss in the switch by 17.38%. hence the efficiency of the ZCS based converter has increased to 92% comparing with the buck converter efficiency 72.97%, the switching losses are reduced by incorporating the L-type ZCS resonant circuit having resonant inductor and resonant capacitor values of

2.62μH and 0.52μF respectively which makes the switch (MOSFET) to turn on and turn off at zero current instants.

4. Conclusion

As to reduce the size/volume of the DC-DC converter it is operated at higher range (kilo-hertz) hertz frequencies. But the operation of the converter at these higher frequencies increases the switching losses density turn-on and turn-off instants. Here in this paper "Zero Current Switching (ZCS) based resonant switched DC-DC converter", has been analysed which incorporates a resonant switch which is a combination of switching device and LC network, is operated at higher frequency of 105KHz at this switching frequency losses are made zero by designing proper values of resonant elements like resonant inductor, and resonant capacitor. With this soft switching of the device in the converter, the average power loss across the switch has been reduced by 17.8% and the efficiency, performance of the converter has been increased

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