A Comparative Study of Performance of ZVS and ZCS Converter Circuits

[1]Mr. Yogesh Likhar, [2]Miss Divya Agrawal

[1]Assistant Professor, [2]Researcher
[1]Electrical Engineering Department,
[1]Guru Nanak Institute of engineering and technology, Nagpur, India

Abstract : ***The comparative result of the performance parameters of resonant converters [ZVS (zero-voltage switching) and ZCS (zero-current switching) with buck converter is presented in this paper. ZVS and ZCS circuits are employed to eliminate the switching losses at high switching frequencies in device using resonance. A zero-current switch shapes the switch current waveform during its conduction time to create a zero-current condition for the switch to turn-off. A zero-voltage switch shapes the switch voltage waveform during the off time to create a zero-voltage condition for the switch to turn-on.***

IndexTerms - Soft switching, resonant converters, zero-voltage switching (ZVS), zero-current switching (ZCS), THD, Power factor.

I. INTRODUCTION

Nowadays in many of the applications like switch mode power supplies (SMPS), the aim is to use as high a switching frequency as possible. High switching frequency makes the unit smaller and reduce the size of the filter elements. The difficulty in increasing the switching frequency to a high level is the switching power losses that occur in the switching element. At each turn-on and turn-off switching, a certain amount of energy is dissipated in the switching element, whose average is known as switching power loss. The switching power loss in device is directly proportional to the switching frequency. On increasing the switching frequency, there is a relative increment in switching power losses. Switching power losses cause higher temperature rise and lower the efficiency of power conversion. Power dissipation in the switch occurs because during switching transition from turn-on to turn-off or vice-versa, voltage across the switch and current through it have non-zero finite values[9] as shown in Fig. 1, thus the product of voltage and current i.e., instantaneous power loss gives a finite value. This stressful switching behaviour of the electronic devices is referred as hard switching. The device stress increases because the switching locus moves through the active region of the safe operating area (SOA).[1]

There are few additional problems associated with hard switching. The reliability of the device can be impaired due to prolonged hard switching operation. High dv/dt, di/dt and parasitic ringing effect at switching of a fast device can create severe electromagnetic interference (EMI) problems, which may effect the converter control circuit and nearby sensitive apparatus. The switching frequency usually falls in the audio frequency range, and thus creates an acoustic noise problem in the machine, which is often objectionable[1].

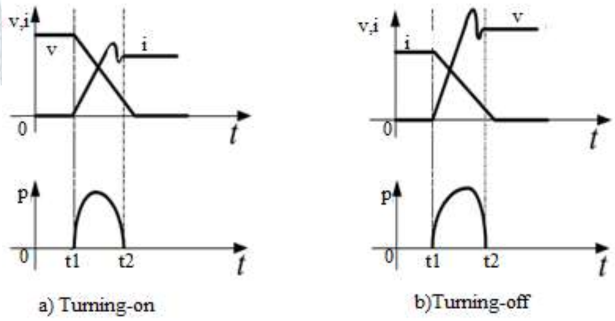

Fig.1 Turning-on and turning-off characteristics during hard switching.

If either of the two, voltage or current, is brought to zero, power losses will become zero as can be seen in Fig. 2, and most of the above harmful effects can be eliminated. This brings the concept of soft switched Zero-voltage switching and Zero-current switching resonant converters. The essence of zero current switch is that by shaping the device's current waveform using the LC resonant tank circuit, a zero current condition is created allowing the device to switch under favourable conditions.[3] .

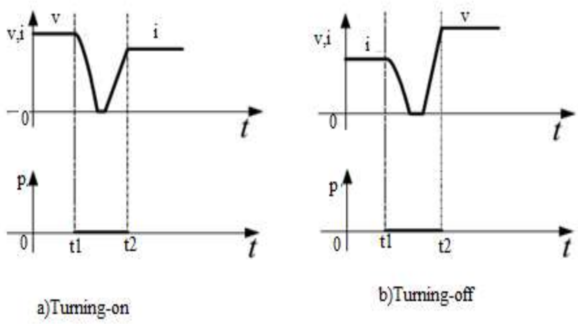

Fig. 2 Turn-on and turn-off characteristics during soft switching.

Similarly, the main idea of zero voltage switching involves the shaping of the device's voltage waveform such that it passes through zero for the switch to turn on. The potential advantage of resonant converter include the natural commutation of power switches, resulting in low switching power losses and reduced component stresses, which in turn results in increased power efficiency and increased switching frequency. By increasing the switching frequency, energy storage elements, such as inductors and capacitors, can be decreased in both value and size. The use of smaller inductors and capacitors result in converters with fast transient capabilities and reduced weight with possible reduction in EMI problems.[2]

II. RESONANT CONVERTERS AND THEIR OPERATIONAL ANALYSIS

A.ZERO-VOLTAGE SWITCHING RESONANT CONVERTER

The switches of ZVS resonant converters turn-on and turn-off at zero voltage[6]. The zero-voltage resonant switch consists of a capacitor C_r connected in parallel with the active switch S_1. The internal switch capacitance is added to C_r and it affects only the resonant frequency, thereby contributing no power dissipation in the switch.

If the switch is implemented with transistor Q_1 and an anti-parallel diode D_1 as shown in Fig. 3, the voltage across C_r is clamped by diode D_1 and switch is operated in half-wave configuration. If diode D_1 is connected in series with Q_1 as shown, the voltage across C can oscillate freely and switch can operate in full-wave configuration[6].

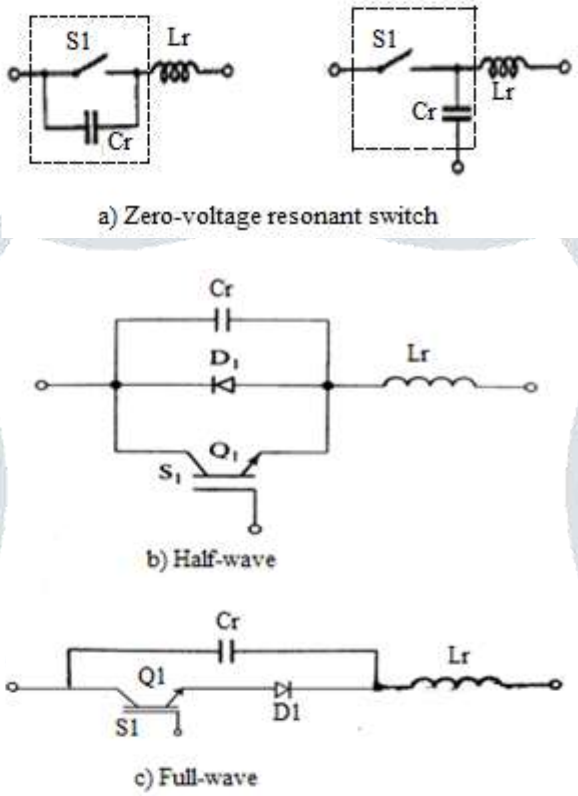

Fig. 3 Switch configuration for ZVS resonant converters.[6]

OPERATIONAL ANALYSIS:

For the detailed steady state analysis of these converters, the switch in the conventional buck converter is replaced by the zero-voltage resonant switch and we obtain a new quasi-resonant ZVS buck converter as shown in Fig. 4.

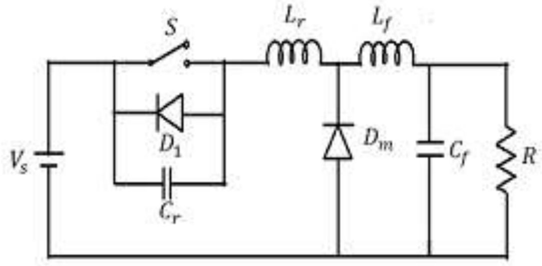

Fig. 4 ZVS resonant buck converter.[5]

To simplify the steady state analysis of the steady state condition for above converter, some assumptions have to be made:

1). The filtering components L_f and C_f are very large when compared to the resonant components L_r and C_r.
2). The output filter L_f-C_f-R is considered as a constant current source, I_o.
3). Ideal switching devices and diodes.
4). Ideal reactive circuit components.

The circuit operation in one switching cycle can be divided into four modes[8]. The parameters are defined as follows-

Characteristic impedance, $Z_o = \sqrt{L_r/C_r}$.
Resonant angular frequency, $\omega_o = 1/\sqrt{L_r C_r}$.
Resonant frequency, $f_r = \omega_o/2\pi$.
Normalised output voltage (voltage gain), $M = V_o/V_s$.
Normalised load, $Q = R/Z_o$.

Normalised switching frequency, F=f_s/f_r.
Switching Period=T_s.

Mode 1:

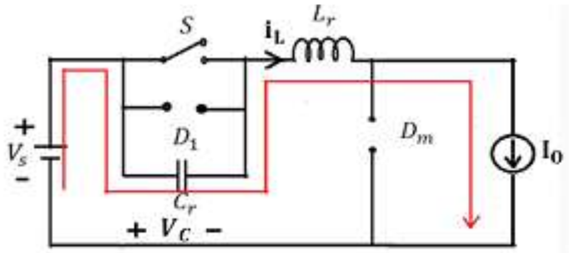

Fig. 5 Equivalent circuit for Mode 1.

This mode is valid for 0≤ t < t_1. In this mode, switch S and diode D_m are off, assuming 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_o. The capacitor voltage V_c rises linearly and it is given as

$$V_c = I_o t/C \qquad (1)$$

This mode ends at time t=t_1, when

$$V_c(t = t_1) = V_s \qquad (2)$$

We can obtain (3) by substituting (2) in (1), i.e.

$$t_1 = \frac{V_s C}{I_o} \qquad (3)$$

Mode 2:

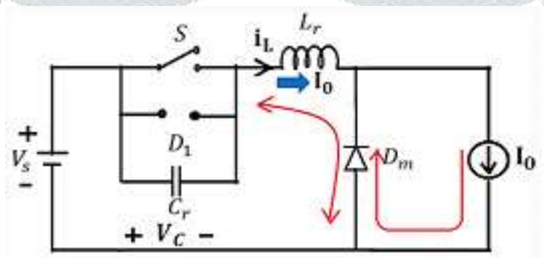

Fig. 6 Equivalent circuit for Mode 2.

This mode is valid for t_1 ≤ t < t_2. The switch S remains off, but diode D_m turns on. The capacitor voltage V_c is given as

$$V_c = V_m sin\omega_o(t - t_1) + V_s \qquad (4)$$

where $V_m = I_o Z_o$ (5)

The inductor current i_L is given by

$$i_L = I_o cos\omega_o(t - t_1) \qquad (6)$$

This mode ends at t= t_2 .

$$V_c(t = t_2) = 0 \qquad (7)$$

Therefore, $t_2 - t_1 = \frac{1}{\omega_0}\sin^{-1}(-V_s / I_o Z_o)$ (8)

$$t_2 - t_1 = \alpha/\omega_o \qquad (9)$$

where $\alpha = \sin^{-1}(-V_s / I_o Z_o)$ (10)

The condition $I_o Z_o > V_s$ must hold to ensure that the operation is under zero-voltage switching.

Mode 3:

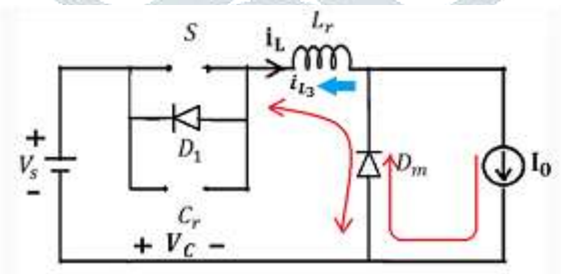

Fig. 7 Equivalent circuit for Mode 3

This mode is valid for t_2≤ t < t_3.

At t=t_2 , capacitor voltage is zero and inductor current start rising linearly and reaches the output current at t=t_3. The body diode turns on to maintain inductor current continuity. S is turned on and the diode D_m remains on until inductor current is less than I_o. The inductor current is given by,

$$i_L(t) = \frac{V_s}{L_r}(t - t_2) + I_o \cos\alpha \qquad (11)$$

This mode ends at time t=t_3.

$$i_L(t = t_3) = I_o \qquad (12)$$

We can obtain (13) by substituting (12) into (11)

$$t_3 - t_2 = \frac{I_o L_r}{V_s}(1 - \cos\alpha) \qquad (13)$$

Mode 4:

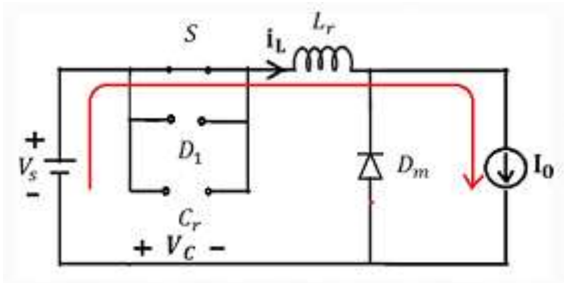

Fig.8 Equivalent circuit for Mode 4

This mode is valid for $t_3 \leq t < t_4$. Switch S is on but D_m is off as inductor current becomes I_o at t= t_3. In this mode switch carries the load current I_o. The switch is turned off at the end of this mode, and the cycle is repeated i.e.,

$$t_4 = T_s - (t_1 + t_2 + t_3) \quad (14)$$

The waveforms for i_L and V_c are shown in Fig. 9 for ZVS resonant buck converter. The peak voltage across the switch is given by

$$V_t(pk) = V_c(pk) = I_o\sqrt{L_r/C_r} + V_s \quad (15)$$

The above equation shows that the peak voltage across the switch V_t(pk) is a function of load current I_o. Thus, the switch voltage varies with the load current and therefore, the load current is maintained constant by using high value of filter inductance. For this reason, ZVS converters are used only for constant-load applications. The turning on of the switch takes place at zero voltage only, otherwise the energy stored in the capacitor C_r will be dissipated in the switch. To avoid this situation, diode D_1 is connected in anti-parallel fashion across the switch, which must conduct before turning on of the switch. The output voltage varies with the switching frequency.

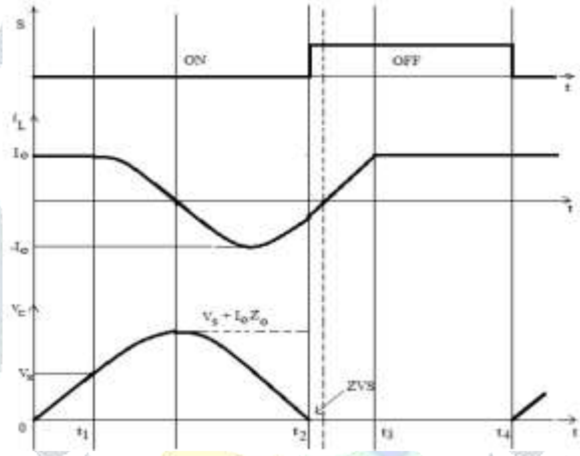

Fig. 9 Steady state waveforms of the ZVS buck converter.[8]

VOLTAGE GAIN:

The input energy to the converter is given as-

$$E_{in} = \int_0^{T_s} V_s \, . \, i_L \, dt \quad (16)$$

$$E_{in} = V_s[\int_0^{t_1} I_o \, dt + \int_{t_1}^{t_2} I_o \cos\omega_o\,(t - t_2)\, dt + \int_{t_2}^{t_3}((V_s/L_r).(t - t_2) + I_o \cos\alpha)dt + \int_{t_3}^{T_s} I_o \, dt. \quad (17)$$

$$E_{in} = V_s[I_o t_1 + \frac{I_o}{\omega_o}\sin\omega_o\,(t_2 - t_1) + \frac{V_s}{2L_r}(t_3 - t_2)^2 + I_o(t_3 - t_2)\cos\alpha + I_o\,(T_s - t_3). \quad (18)$$

By substituting the values from (3), (9) and (13), we get,

$$E_{in} = V_s I_o[\frac{C_r V_s}{I_o} + \frac{\sin\alpha}{\omega_o} + \frac{I_o L_r}{2V_s} - \frac{I_o L_r}{2V_s}(\cos\alpha)^2 + T_s - t_3]. \quad (19)$$

Output energy is given as,

$$E_o = \int_0^{T_s} I_o V_o dt \quad (20)$$

$$E_o = I_o V_o T_s \quad (21)$$

By using energy balance concept,

$$E_{in} = E_o \quad (22)$$

This gives,

$$M = 1 - \frac{F}{2\pi}\left[\frac{Q}{2M} + \frac{M}{Q} * (1 - \cos\alpha) + \alpha\right] \quad (23)$$

A plot of the control characteristic curve of M vs. F under various normalised loads is given in Fig. 10.[8][10]

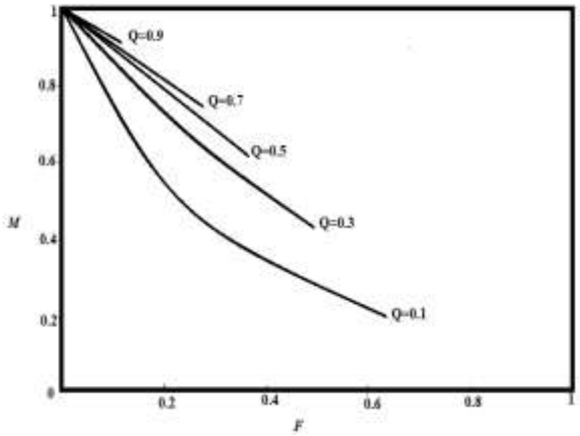

Fig.10 Control characteristic curve of M Vs F for ZVS Buck converter.

B.ZERO-CURRENT SWITCHING RESONANT CONVERTER:

The switches of zero current switching converter turn on and turnoff at zero current[6]. In a zero-current resonant switch, an inductor L_r is connected in series with the power switch S in order to achieve zero-current switching. If the switch S is a unidirectional switch, the switch current is allowed to resonate in the positive half cycle only. The resonant switch is said to be operated in half-wave mode. If a diode is connected in anti-parallel with the switch, the switch current can flow in both directions. In this case, resonant switch can operate in full-wave mode as shown in Fig. 11.

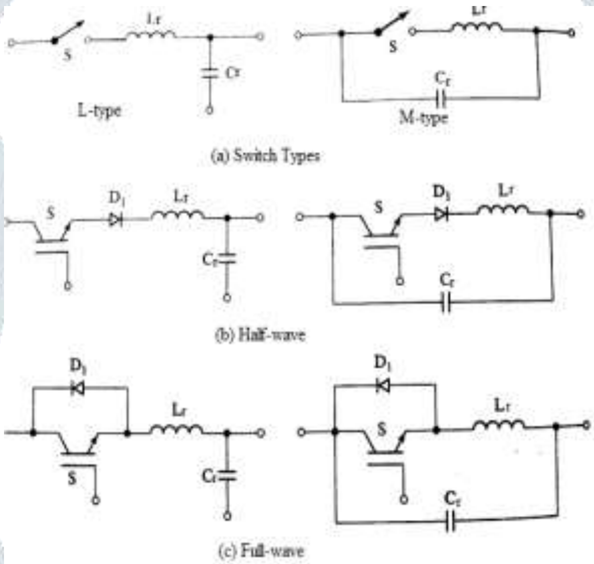

Fig. 11 Switch configuration for ZCS resonant converter.[6]

Zero-current resonant switch is classified into two types-L type and M type. In both the types, inductor L_r limits the di/dt of the switch current and L_r and C_r constitute a series resonant circuit. ZCS resonant converter is the dual of ZVS resonant converter.

<u>OPERATIONAL ANALYSIS:</u>

Fig. 12 shows a ZCS resonant buck converter.[8]

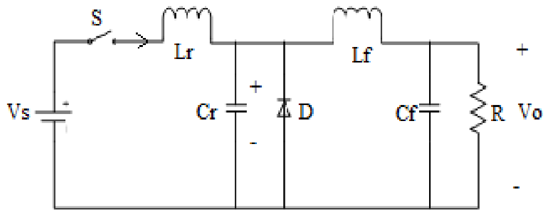

Fig. 12 ZCS resonant buck converter.

There are four modes of operation[8]. L_f is assumed to be very large as compared to L_r and C_r so that its current is considered to be constant and equal to I_o.

Mode 1:

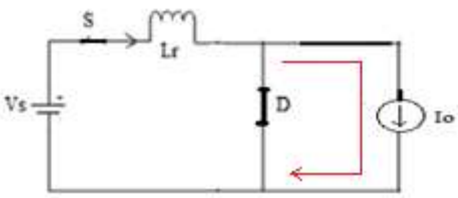

Fig. 13 Equivalent circuit for Mode 1

This mode is valid for $0 \le t \le t_1$. Switch S is turned on at t=0, and diode D must have been conducting for t < 0 to carry output inductor current. The outputcurrent is equal to constant current source Io. Capacitor voltage is zero and input voltage is equal to inductor voltage given by-

$$L_r \frac{di_L}{dt} = V_s \quad (24)$$

$$i_L = V_s t / L_r \quad (25)$$

At t=t_1, $i_L = I_o$ (26)

Therefore, $t_1 = I_o L_r / V_s$ (27)

Mode 2:

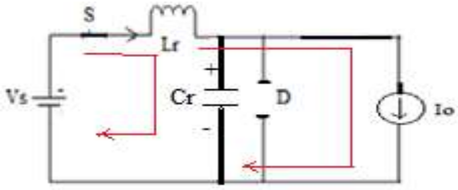

Fig. 14 Equivalent circuit for Mode 2

This mode is valid for $t_1 \le t < t_2$. At t_1 , inductor current is I_o and diode D is open circuited resulting in a resonant stage between L_r and C_r. During t_1 to t_2, switch S remains on but diode is off. The inductor current and capacitor voltage are given by,

$$i_L = I_o + \frac{V_s}{Z_o} \sin \omega_o (t - t_1) \quad (28)$$

$$V_c = V_s [1 - \cos \omega_o (t - t_1) \quad (29)$$

At t=t_2, $i_L = 0$. Therefore,

$$t_2 - t_1 = \frac{1}{\omega_o} \sin^{-1}(-I_o Z_o / V_s) = \frac{\alpha}{\omega_o} \quad (30)$$

where, $\alpha = \sin^{-1}(-I_o Z_o / V_s)$ (31)

The condition $I_o Z_o < V_s$ must hold to ensure that the operation is under zero-current switching.

Mode 3:

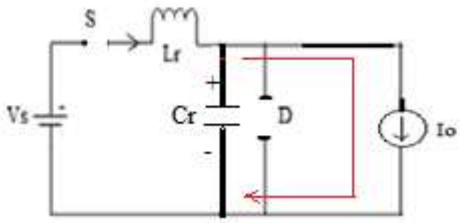

Fig. 15 Equivalent circuit for Mode 3

This mode is valid for $t_2 \le t < t_3$. Resonance stops and and at t=t_2, inductor current becomes zero and the switch S is turned off. The capacitor discharges linearly to zero. The diode remains off. The capacitor current equals I_o and capacitor voltage is obtained as-

$$V_c = -\frac{I_o}{C_r} * (t - t_2) + V_s [1 - \cos \omega_o (t_2 - t_1)] \quad (32)$$

At t=t_3, capacitor voltage becomes zero.

$$t_3 - t_2 = C_r V_s / I_o [1 - \cos \omega_o (t_2 - t_1) \quad (33)$$

Mode 4:

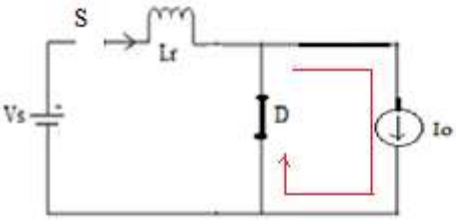

Fig. 16 Equivalent circuit for Mode 4

This mode is valid for $t_3 \le t < t_4$.

Switch S remains off but diode starts conducting at t=t_3. There will be no power transfer at this mode. By turning on switch at T_s, the cycle will repeat again.

Duration for this mode, $t_4 = T_s - (t_1 + t_2 + t_3)$. (34)

The waveforms for i_L and V_c are given in Fig. 17.

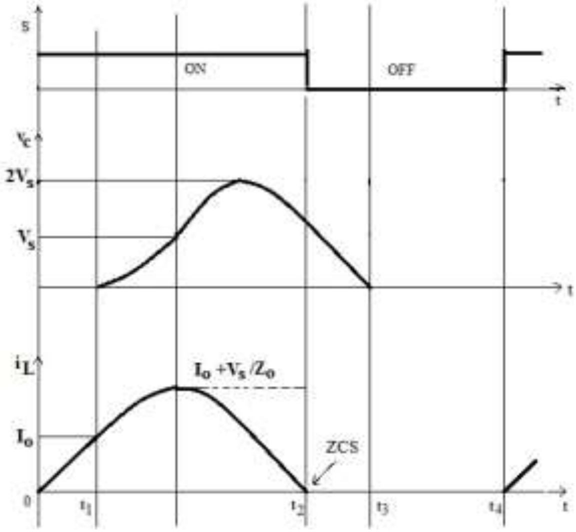

Fig. 17 Steady state waveforms for ZCS boost converter.[8][7]

<u>VOLTAGE GAIN</u>:

The input energy is given as-

$$E_{in} = \int_0^{T_s} V_s I_s dt \quad (35)$$

$$E_{in} = \int_0^{t_1} V_s . i_L dt + \int_{t_1}^{t_2} V_s . i_L dt \quad (36)$$

$$E_{in} = V_s[\frac{{I_o}^2 L_r}{2V_s} + \frac{I_o\alpha}{\omega_o} + \frac{V_s}{Z_o\omega_o}(1-\cos\alpha) \quad (37)$$

The output energy is given by-

$$E_o = \int_o^{T_s} I_o V_o dt \quad (38)$$

$$E_o = I_o V_o T_s \quad (39)$$

By using energy balance concept,

$$E_{in} = E_o \quad (40)$$

$$M = \frac{F}{2\pi}[\frac{M}{2Q} + \alpha + \frac{Q}{M}(1-\cos\alpha)] \quad (41)$$

A plot of control characteristic curve of M vs. F is shown in Fig. 18.

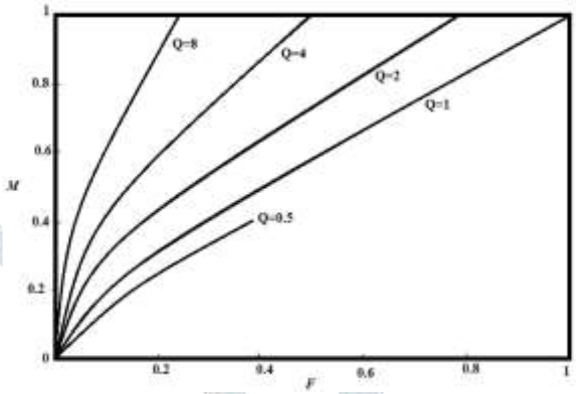

Fig.18 Control characteristic curve of M Vs F for ZCS buck converter.[8][10]

III. DESIGN CONSIDERATION

To design the resonant converter, input and output voltages, output current and switching frequency must be considered[8]. These parameters of the designed converter are shown in TABLE.1.

TABLE 1

DESIGN CONSIDERATION

Symbol	Quantity	Value
V_s	**Input voltage**	**15V**
V_o	**Output voltage**	**7.5V**
I_o	**Output current**	**1A**
R	**Load resistance**	**7.5Ω**
f_s	**Switching frequency**	**25KHz**

In ZVS resonant buck converter, considering M= 0.5 and F= 0.498, from the plot of control characteristic curve of M vs. F, Q= 0.45.

$$Q = R/Z_o \quad (42)$$

$$\sqrt{\frac{L_r}{C_r}} = \frac{R}{Q} = 16.66 \quad (43)$$

$$\frac{L_r}{C_r} = 277.78 \quad (44)$$

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} = \frac{f_s}{F} = \frac{25000}{0.498} \quad (45)$$

$$L_r C_r = 10.05 * 10^{-12} \quad (46)$$

Solving (44) and (46) gives,

$$C_r = 0.1902\mu F \quad (47)$$

$$L_r = 0.052mH \quad (48)$$

Condition $I_o Z_o > V_s$ is satisfied for zero voltage switching operation.

$$t_1 = \frac{C_r V_s}{I_o} = 2.85\mu s \quad (49)$$

$$t_2 - t_1 = \frac{1}{\omega_o}[\pi + \sin^{-1}(\frac{V_s}{I_o Z_o})]$$

$$t_2 = 13.511\mu s \quad (50)$$

Duty cycle, D=$\frac{T_{on}}{T_s} = \frac{T_s - t_2}{T_s}$ = 0.591. (51)

For same value of M and F, Q= 0.5549 is obtained from the control characteristic curve for ZCS resonant buck converter.

$$Q = R/Z_o \quad (52)$$

$$\sqrt{\frac{L_r}{C_r}} = \frac{R}{Q} = 13.52 \quad (53)$$

$$\frac{L_r}{C_r} = 182.68 \quad (54)$$

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} = \frac{f_s}{F} = \frac{25000}{0.498} \quad (55)$$

$$L_r C_r = 10.05 * 10^{-12} \quad (56)$$

Solving (54) and (56) gives,

$$C_r = 0.235\mu F \quad (57)$$

$$L_r = 0.0428mH \quad (58)$$

Condition $I_o Z_o < V_s$ is satisfied for zero current switching operation.

$$t_1 = \frac{L_r I_o}{V_s} = 2.85\mu s \quad (59)$$

$$t_2 - t_1 = \frac{1}{\omega_o}[\pi + \sin^{-1}(\frac{Z_o I_o}{V_s})]$$

$$t_2 = 16.37\mu s \quad (60)$$

Duty cycle, D=$\frac{T_{on}}{T_s} = \frac{t_2}{T_s}$ = 0.4092. (61)

IV. SIMULATION STUDY

Simulation study of the designed resonant converters has been performed in MATLAB simulation software. To compare resonant converters in terms of power factor and THD, these converters are fed with a rectified voltage of 15 V as input. The rectifier output before feeding to the converters is filtered through a low pass filter with elements value as L=1mH and C= 25 mF. The rectifier input is taken to be as 16.45V, as there occur voltage drop across filtering inductor.

The output voltage and switch current waveforms for buck converter are shown in Fig. 19. The switches in simulation model are ideal.

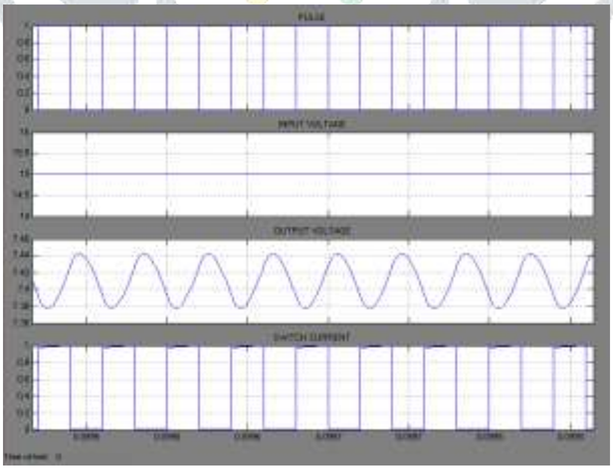

Fig.19 Output voltage and switch current waveforms for buck converter with 15 V input.

The waveforms of resonant inductor current, resonant capacitor voltage and output voltage for ZVS resonant buck converter and ZCS resonant buck converter with 15V input has been shown in Fig.20 and Fig.21, respectively.

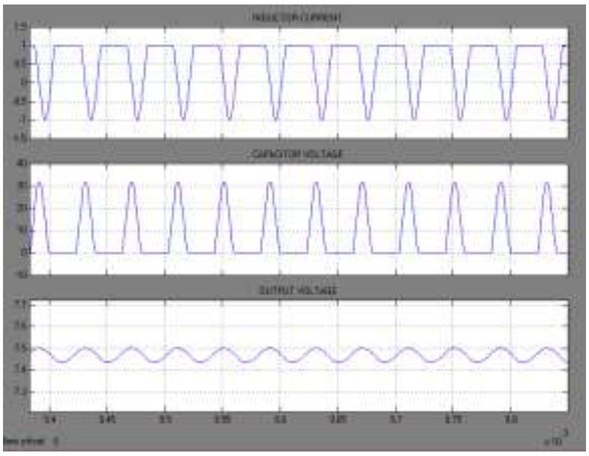

Fig.20 Output waveforms for ZVS resonant buck converter with 15 V input.

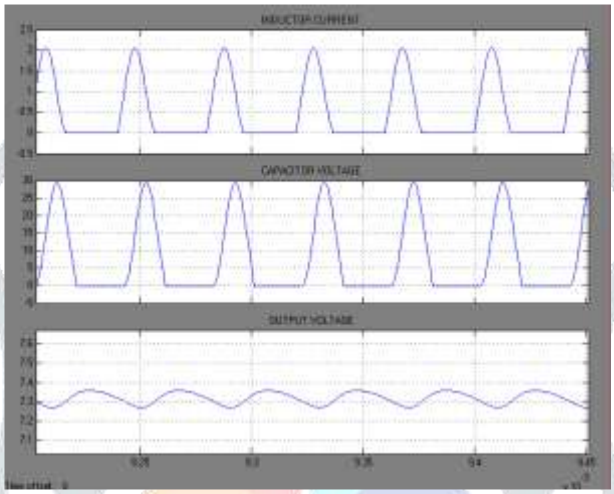

Fig. 21 Output waveforms for ZCS resonant buck converter with 15V input.

V. COMPARISON BETWEEN ZVS AND ZCS RESONANT CONVERTER

Both of these techniques require a variable frequency control to regulate the output voltage.

In ZCS, the switch is required to conduct a peak current that is higher than the load current by an amount V_s/Z_o. For natural turn-off of the switch at zero current, the load current I_o must not exceed V_s/Z_o. In ZVS, the switch is required to withstand a forward voltage that is higher than V_s by an amount Z_oI_o. For zero-voltage turn-on of the switch, the load current must be greater than V_s/Z_o. Therefore, ZVS is limited to an essentially constant load application.

ZCS can eliminate the switching losses at turn-off and reduce the switching losses at turn-on. When the power MOSFET's are used for ZCS, the energy stored in the device's capacitance is dissipated during turn-on. This capacitive turn-on loss is proportional to the switching frequency. ZVS eliminates the capacitive turn on loss. It is suitable for high frequency operation.

ZCS operates with a constant on-time control, whereas ZVS operates with a constant off-time control [6],[7].

The comparison between buck converter, ZVS resonant buck converter and ZCS resonant buck converter on the basis of performance parameters as obtained from simulation results for fundamental frequency of 50Hz, has been shown in Table. 2.

TABLE 3

	OUTPUT VOLTAGE RIPPLE (V)	THD (%)	POWER FACTOR
BUCK CONVERTER	0.065	94.02	0.927
ZVS BUCK CONVERTER	0.065	93.70	0.9274
ZCS BUCK CONVERTER	0.09	94.34	0.9188

V. CONCLUSION

ZVS is preferable over ZCS at high switching frequencies. The reason has to do with the internal capacitances of the switch. When the switch turns on at zero-current but a finite voltage, the charge on the internal capacitances is dissipated in the switch. This loss becomes significant at very high switching frequencies. However, no such loss occurs if the switch turns on at a zero voltage.

Also ZVS converter has output voltage ripple same as conventional buck converter, whereas ZCS converter increases the ripple in the output voltage.

For favourable operation, it is required to have less distortion in the waveform. ZVS has less harmonic distortion for input current but in ZCS, harmonic distortion is seen to be slightly more than that of conventional buck converter. ZVS buck converter has power factor nearly equal to the conventional buck converter. ZCS buck converter lowers the power factor.

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