A Comparative Study of Performance of ZVS and ZCS Converter Circuits

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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].

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]

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].

![Switch configuration for ZVS resonant converters.][1]

**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.

![ZVS resonant buck converter.][2]

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 \( L_r-C_r-R \) 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, \( \omega_0 = 1/\sqrt{L_rC_r} \).
- Resonant frequency, \( f_r = \omega_0/2\pi \).
- Normalised output voltage (voltage gain), \( M=V_o/V_i \).
- Normalised load, \( Q=R/Z_o \).
Normalised switching frequency, \( F = f_s / f_c \)
Switching Period = \( T_c \)

**Mode 1:**

![Fig. 5 Equivalent circuit for Mode 1.](image)
This mode is valid for \( 0 \leq t < t_1 \). 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
\[
V_c = I_o t / C 
\]  
(1)
This mode ends at time \( t = t_1 \), when
\[
V_c(t = t_1) = V_s 
\]  
(2)
We can obtain (3) by substituting (2) in (1), i.e.
\[
t_1 = \frac{V_c}{I_o} 
\]  
(3)

**Mode 2:**

![Fig. 6 Equivalent circuit for Mode 2.](image)
This mode is valid for \( t_1 \leq t < t_2 \). The switch \( S \) remains off, but diode \( D_m \) turns on. The capacitor voltage \( V_c \) is given as
\[
V_c = V_m \sin \omega_o (t - t_1) + V_s 
\]  
(4)
where \( V_m = I_o Z_o \)  
(5)
The inductor current \( i_L \) is given by
\[
i_L = I_o \cos \omega_o (t - t_1) 
\]  
(6)
This mode ends at \( t = t_2 \)
\[
V_c(t = t_2) = 0 
\]  
(7)
Therefore, \( t_2 - t_1 = \frac{1}{\omega_o} \sin^{-1} \left( -\frac{V_s}{I_o Z_o} \right) \)  
(8)
\[
t_2 - t_1 = \alpha / \omega_o 
\]  
(9)
where \( \alpha = \sin^{-1} \left( -\frac{V_s}{I_o Z_o} \right) \)  
(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](image)
This mode is valid for \( t_2 \leq t < t_3 \).
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,
\[
i_L(t) = \frac{V_s}{I_o} (t - t_2) + I_o \cos \alpha 
\]  
(11)
This mode ends at time \( t = t_3 \)
\[
i_L(t = t_3) = I_o 
\]  
(12)
We can obtain (13) by substituting (12) into (11)
\[
t_3 - t_2 = \frac{I_o \alpha}{V_s} (1 - \cos \alpha) 
\]  
(13)

**Mode 4:**
This mode is valid for \( t_2 \leq t < t_4 \). 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.,

\[
t_4 = \frac{t_2}{t_1 + t_2 + t_3}
\]

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

\[
V_s(pk) = \sqrt{L_r/C_r + V_c}
\]

The above equation shows that the peak voltage across the switch \( V_s(pk) \) 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.

\[
V_{OUT} = \frac{V_s}{D}
\]

### VOLTAGE GAIN:

The input energy to the converter is given as:

\[
E_{in} = \int_0^{t_2} i_L \, dt
\]

\[
E_{in} = V_s \int_0^{t_1} I_o \, dt + \int_0^{t_2} I_o \cos \omega_o (t - t_2) \, dt + \int_{t_2}^{t_3} (V_s/L_r) \cdot (t - t_2) + I_o \cos \alpha) \, dt + \int_{t_3}^{t_4} I_o \, dt.
\]

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

\[
E_{in} = V_s I_o \left[ t_2 \cos \omega_o (t_2 - t_1) + \frac{V_s}{2L_r} (t_3 - t_2)^2 + I_o (t_3 - t_2) \cos \alpha + I_o (T_3 - t_3). \right]
\]

Output energy is given as,

\[
E_o = \int_0^{t_2} i_o \cdot V_o \, dt
\]

\[
E_o = I_o V_s t_2
\]

By using energy balance concept,

\[
E_{in} = E_o
\]

This gives,

\[
M = 1 - \frac{K}{2T} + \frac{M}{Q} (1 - \cos \alpha) + \alpha
\]

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 turn off 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 \( \text{di/dt} \) 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.

**OPERATIONAL ANALYSIS:**

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

There are four modes of operation [8]. \( L_d \) 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 $0 \leq t \leq t_1$. Switch $S$ is turned on at $t=0$, and diode $D$ must have been conducting for $t < 0$ to carry output inductor current. The output current is equal to constant current source $I_0$. Capacitor voltage is zero and input voltage is equal to inductor voltage given by-

$$L_r \frac{di_L}{dt} = V_s$$  \hspace{1cm} (24)

$$i_L = V_s t / L_r$$  \hspace{1cm} (25)

At $t=t_1$, $i_L = I_o$  \hspace{1cm} (26)

Therefore, $t_1 = I_o L_r / V_s$  \hspace{1cm} (27)

**Mode 2:**

![Fig. 14](image1.png)

This mode is valid for $t_1 \leq t < t_2$. At $t=t_1$, 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,

$$i_L = I_o + \frac{V_s}{Z_o} \sin \omega_o (t - t_1)$$  \hspace{1cm} (28)

$$V_c = V_o [1 - \cos \omega_o (t - t_1)]$$  \hspace{1cm} (29)

At $t=t_2$, $i_L = 0$. Therefore, $t_2 - t_1 = \frac{1}{\omega_o} \sin^{-1}(-I_o Z_o / V_s)$  \hspace{1cm} (30)

where, $\alpha = \sin^{-1}(-I_o Z_o / V_s)$  \hspace{1cm} (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](image2.png)

This mode is valid for $t_2 \leq t < t_3$. Resonance stops 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-

$$V_c = \frac{1}{C_r} \ast (t - t_2) + V_o [1 - \cos \omega_o (t_2 - t_1)]$$  \hspace{1cm} (32)

At $t=t_3$, capacitor voltage becomes zero.

$$t_3 - t_2 = C_r V_o / I_o [1 - \cos \omega_o (t_2 - t_2)]$$  \hspace{1cm} (33)

**Mode 4:**

![Fig. 16](image3.png)

This mode is valid for $t_3 \leq t < t_4$. 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, $t_4 = T_s - (t_1 + t_2 + t_3)$.  \hspace{1cm} (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]

### Voltage Gain:

The input energy is given as:

\[ E_{in} = \int_0^{t_1} V_i I_0 dt \]

\[ E_{in} = \int_0^{t_1} V_s i_L \, dt + \int_0^{t_2} V_s i_L \, dt \]

\[ E_{in} = V_i \left[ \frac{\alpha}{2V_s} + \frac{V_s}{Z_ao_0} \right] (1 - \cos \alpha) \]

The output energy is given by:

\[ E_o = \int_0^{t_2} I_o V_o dt \]

\[ E_o = I_o V_o T_s \]

By using energy balance concept,

\[ E_{in} = E_o \]

\[ M = \frac{f_s}{2\pi} \left[ \frac{M}{2Q} + \frac{Q}{M} (1 - \cos \alpha) \right] \]

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>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_i</td>
<td>Input voltage</td>
<td>15V</td>
</tr>
<tr>
<td>V_o</td>
<td>Output voltage</td>
<td>7.5V</td>
</tr>
<tr>
<td>I_o</td>
<td>Output current</td>
<td>1A</td>
</tr>
<tr>
<td>R</td>
<td>Load resistance</td>
<td>7.5\Omega</td>
</tr>
<tr>
<td>f_s</td>
<td>Switching frequency</td>
<td>25KHz</td>
</tr>
</tbody>
</table>

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.

\[ Q = \frac{R}{Z_0} \]

\[ \sqrt{\frac{L_c}{C_r}} = \frac{R}{Q} = 16.66 \]
\[
\frac{L_r}{C_r} = 277.78
\]  
(44)
\[
f_r = \frac{1}{2\pi\sqrt{L_rC_r}} = \frac{f}{P} = \frac{25000}{0.498}
\]  
(45)
\[
L_rC_r = 10.05 \times 10^{-12}
\]  
(46)
Solving (44) and (46) gives,
\[
C_r = 0.1902\mu F
\]  
(47)
\[
L_r = 0.052 mH
\]  
(48)
Condition \(I_oZ_o>V_o\) is satisfied for zero voltage switching operation.
\[
t_1 = \frac{L_rV_o}{I_o} = 2.85\mu s
\]  
(49)
\[
t_2 - t_1 = \frac{1}{\omega_o} [\pi + \sin^{-1}(\frac{V_o}{I_o\omega_o})]
\]  
(50)
Duty cycle, \(D = \frac{t_2}{t_s} = 0.591\).  
(51)
For same value of \(M\) and \(F\), \(Q = 0.5549\) is obtained from the control characteristic curve for ZCS resonant buck converter.
\[
Q = R/Z_o
\]  
(52)
\[
\sqrt{\frac{L_r}{C_r}} = \frac{R}{Q} = 13.52
\]  
(53)
\[
\frac{L_r}{C_r} = 182.68
\]  
(54)
\[
f_r = \frac{1}{2\pi\sqrt{L_rC_r}} = \frac{f}{P} = \frac{25000}{0.498}
\]  
(55)
\[
L_rC_r = 10.05 \times 10^{-12}
\]  
(56)
Solving (54) and (56) gives,
\[
C_r = 0.235\mu F
\]  
(57)
\[
L_r = 0.0428 mH
\]  
(58)
Condition \(I_oZ_o<V_o\) is satisfied for zero current switching operation.
\[
t_1 = \frac{L_rI_o}{V_o} = 2.85\mu s
\]  
(59)
\[
t_2 - t_1 = \frac{1}{\omega_o} [\pi + \sin^{-1}(\frac{I_o\omega_o}{V_o})]
\]  
(60)
Duty cycle, \(D = \frac{t_2}{t_s} = 0.4092\).  
(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 \(L = 1\) mH 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.
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 \( Z_o I_o \). 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>
<thead>
<tr>
<th>TABLE 3</th>
<th>OUTPUT VOLTAGE RIPPLE (V)</th>
<th>THD (%)</th>
<th>POWER FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUCK CONVERTER</td>
<td>0.065</td>
<td>94.02</td>
<td>0.927</td>
</tr>
<tr>
<td>ZVS BUCK CONVERTER</td>
<td>0.065</td>
<td>93.70</td>
<td>0.9274</td>
</tr>
<tr>
<td>ZCS BUCK CONVERTER</td>
<td>0.09</td>
<td>94.34</td>
<td>0.9188</td>
</tr>
</tbody>
</table>

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.

REFERENCES


