An improved zero-voltage zero-current transition boost converter employing L-C-S resonant network

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ABSTRACT
An improved zero-voltage zero-current transition boost converter (IZVZCTBC) is introduced. This converter is basically a fourth-order DC-DC converter wherein a L-C-S (Inductor–Capacitor–Switch) resonant circuit is embedded for soft-switching. L-C-S tank network is the modified version of conventional ZVZCT switch cell. The main feature of L-C-S tank circuit is to enhance the performance of zero-voltage zero-current transition boost converter in terms of eliminating the high current stress, decreasing the switching losses and increasing the efficiency of converter. This converter exhibits both zero-voltage turn on and zero-current turn off switching characteristics based on the gating signals applied to switches. The principle of operation and time domain expressions of IZVZCT boost converter with L-C-S cell are presented. For the closed loop operation, digital controller is designed and the performance of the controller has been validated through simulation for different line and load variations. The mathematical and theoretical analysis is verified accurately by a 12-24 V, 30 W converter through PSIM simulation software and the results ensures that overall efficiency of the converter has improved to 97% along with elimination of current stress.

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1. INTRODUCTION
Modern era deals with new power electronic technologies to satisfy the needs and requirements of industries. High frequency DC-DC converters are predominantly utilized to serve industrial needs. Converters with high frequency has more advantages compared to low frequency operations, increased frequency provides large power density, quick response, reduction in physical size, cost and weight of reactive elements. Besides these merits, it also offers demerits such as high switching losses and stress, poor efficiency and electromagnetic interference noise. These difficulties can be rectified with soft-switching technologies and they are of mainly four types, i) Zero-Voltage Switching, ii) Zero-Current Switching, iii) Zero-Voltage Transition, iv) Zero-Current Transition. Among the four, first two switching techniques mainly deals with increasing efficiency and reducing the losses but it does not account on switch stress, but the second two transition techniques provides high efficiency, reduced losses and switch stress. Apart from the
mentioned techniques, there is another technique that combines both ZVT and ZCT methods, called as ZVZCT technique which offers advantages of both the techniques [1-10].

An active snubber cell based ZVZCT boost converter was introduced wherein the snubber cell plays a role in providing ZVT and ZCT for main switch of the converter [1]. A ZVT/ZCT/PWM snubber cell based converter was reported in which the cell offers ZVT turn on and ZCT turn off for main switch by employing single quasi resonating network [2]. A snubber cell based ZVT/ZCT DC-DC converter was introduced, where additional current/voltage stress are neglected on main switch and current stress on additional switch is reduced by coupling inductance [3]. A new snubber cell based ZVT-ZCT converter was presented which increases the converter efficiency, power density and reduces the EMI noise [4]. In ZCZVT quasi-resonant buck converter, where an active snubber network renders ZVT turn on and ZCT turn off collectively for the switches present in the converter without any other voltage and current stress [5]. A zero-voltage/zero-current transition converter using snubber was developed in [6], where the operation was verified on a high power converter wherein a high efficiency of about 98% was obtained at 100 kHz switching frequency.

A three-level half bridge ZVZCS PWM DC/DC converter was introduced wherein ZVS and ZCS are achieved through parasitic inductance of transformer, snubber capacitors and tapped inductor type smoothing filter, this converter does not possess ancillary resonant circuit to obtain soft-switching [7]. A new ZVZCT boost converter employing a coupling inductor was developed, in which the switches and diodes undergo soft-switching and improves the efficiency with reduced circulating current due to the coupling effect [8]. An optimized ZVZCT boost converter was achieved by using a coupling inductor, the main advantage of this topology is that the steady-state condition of main switch can be optimized by fixing the coupling inductance ratio for each desired load [9]. A soft-switching boost converter with coupled inductor and an extra switch was analyzed, here the coupled-inductor delivers the energy to the load, which minimizes the auxiliary switch current stress and also helps in improving the efficiency of converter [10]. Voltage-multiplier cell and coupled-inductors integrated high static gain DC/DC soft-switching converter was presented, in which the multiplier cell along with coupled-inductors play a vital role in reducing switch voltage, conduction losses and it also improves the efficiency [11]. A magnetically coupled auxiliary network based ZCZVT inverter is proposed in [12], which overcomes the reactive energy problem and improves the efficiency.

A ZCZVT commutation cell based DC/DC PWM converter was addressed [13] which offers the benefits of both soft-transition methods. A commutation cell based true ZCZVT DC/DC PWM converter was explained in which commutation cell offers ZCS and ZVS for main switch during turn off and turn on simultaneously [14]. A high efficient ZVZCT converter for battery cell equalization was addressed wherein by employing the volt-sec balance principle of inductor and transformer coupling, the battery cells are equalized and by including ancillary resonant network at the main switching devices, ZVS and ZCS are achieved with elimination of losses [15]. A synchronous rectification based ZCZVT forward converter was introduced, wherein the converter is operated with synchronous rectification to minimize conduction losses of the rectifier at load side and to improve the overall efficiency to 89% [16]. A soft-switching ZCZVT boost power converter was analyzed and a classical controller was designed in order to neglect source voltage variation and to attain load voltage regulation [17].

A zero-voltage transition fifth-order boost converter undergoes soft-switching for the switching devices and also voltage-mode digital controller for the converter have been discussed in [18]. A LCLC resonant network based bidirectional soft-switching DC/DC converter was analyzed, this converter is an improved version of traditional bidirectional converter by replacing the isolation transformer with LCLC resonance circuit to achieve high efficiency with high boost ratios [19]. An enhanced zero-voltage transition boosting converter was introduced in which a LCS resonant cell is employed to attain the soft-switching of the devices, to improve efficiency and to eliminate the peak current stress of the converter [20].

A soft-switching interleaved boost converter for fuel cell application was proposed, in which two similar boost converters are connected in parallel and controlled by interleaved switching signals. This converter is widely used for high efficiency fuel cell power systems in which it improves the electrical performance, efficiency and it also reduces the switching loss, size and weight of the converter [21]. A new zero voltage transition bidirectional DC-DC converter was introduced for battery back-up systems in hybrid electric vehicles, which reduces the turn-on switching losses, switch current stress and improves the efficiency [22]. A review of various soft-switching techniques was carried out based on the topology, resonant circuit location, performance characteristics and principle of operation. In addition, converters area of application, merits and demerits are also addressed [23].
2. ANALYSIS AND PRINCIPLE OF OPERATION OF IZVZCTBC

The proposed Improved Zero-Voltage Zero-Current Transition Boost Converter is presented in Figure 1. Normally, an auxiliary network comprising of additional switch, diode, inductor and capacitor are sufficient to realize the resonance phenomenon in the converter which offers higher efficiency and reduced switching losses, but there is a huge current stress and conduction losses across the main switch. In order to avoid this, a slight modification in the auxiliary network is done by adding one more series inductor with main switch and the proposed L-C-S resonant network comprised of auxiliary switch (Saux), auxiliary diode (Daux), resonating inductor (Lr), resonating capacitor (C) and a main series inductor (Lmain). The resonance is taking place among the auxiliary soft-switching capacitor (C) and energy transferring inductor (Lr). Also, for a short interval of period, the resonating capacitor exchanges energy with the parallel combination of Lr and Lmain. Proper selection of C, Lr and Lmain will be vital for achieving the IZVZCT operation.

Following are the assumptions to be made in order to make the analysis simpler. At input side, the existence of huge inductor (L1) in series with voltage source has been substituted with the magnitude of Ig (constant source current). At load side, the existence of huge capacitor (C0) in parallel with load has been substituted with the magnitude of V0 (constant source voltage). It is assumed that all the switching devices and energy storing components are ideal. The status of individual switching devices in each mode of IZVZCT operation is given in the Table 1. Waveforms of voltages and currents across/through the different switches during one cycle of operation are shown in Figure 2. Figures 3 & 4 depicts the structural variations in ZVT/ZCT operations.

Table 1. Status of individual switching devices in each mode of IZVZCT operation

| Mode of operation | Time duration | S_main | S_aux | D_main | D_aux |
|-------------------|---------------|--------|-------|--------|-------|
| Mode 1            | t0≤t≤t1       | X      | ✓     | ✓      | ✓     |
| Mode 2            | t1≤t≤t2       | X      | ✓     | ✓      | ✓     |
| Mode 3            | t2≤t≤t3       | ✓      | ✓     | ✓      | ✓     |
| Mode 4            | t3≤t≤t4       | X      | ✓     | ✓      | ✓     |
| Mode 5            | t4≤t≤t5       | X      | ✓     | ✓      | ✓     |
| Mode 6            | t5≤t≤t6       | ✓      | ✓     | ✓      | ✓     |
| Mode 7            | t6≤t≤t7       | ✓      | ✓     | ✓      | ✓     |
| Mode 8            | t7≤t≤t8       | ✓      | ✓     | ✓      | ✓     |
| Mode 9            | t8≤t≤t9       | ✓      | ✓     | ✓      | ✓     |
| Mode 10           | t9≤t≤t10      | ✓      | ✓     | ✓      | ✓     |
| Mode 11           | t10≤t≤t11     | ✓      | ✓     | ✓      | ✓     |
| Mode 12           | t11≤t≤t12     | X      | ✓     | ✓      | ✓     |
| Mode 13           | t12≤t≤T        | X      | ✓     | ✓      | ✓     |

![Figure 1. Proposed Improved ZVZCT Boost Converter](image-url)
Figure 2. Voltage/Current waveforms of various switching devices in IZVZCT operation

Figure 3. Structural variations in ZVT operation

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Figure 4. Structural variations in ZCT operation

2.1. Operating modes in a switching cycle

Mode I ($t_0 - t_1$):
Prior to this mode, the circuit was in freewheeling mode with main diode alone conducting. Before triggering main switch, trigger the auxiliary switch in subsequent time which reduces the voltage across main switch to become zero, before it turns ON (with ZVS condition). The duration of this mode of operation is given by $t_1$.
Initial conditions:

$$ v_{C_r}(0) = V_o, i_{t_1}(0) = 0, i_{D_A}(0) = 0 $$

$$ t_1 = \frac{1}{\omega_r} \sin^{-1} \left( \frac{V_o}{2I_0} \right) \quad (1) $$

Mode II ($t_1 - t_2$):
Initial conditions:

$$ v_{C_r}(0) = V_o \cos[\omega_r(t_1 - t_0)], \quad v_{C_r}^{-1}(0) = -V_o \sin[\omega_r(t_1 - t_0)], \quad i_{t_1}(0) = \frac{V_o}{\omega_r} \sin[\omega_r(t_1 - t_0)], $$

$$ i_{D_A}(0) = \frac{I_g}{\omega_r} $$

The time domain equation of this mode is,

$$ t_2 = t_1 + \left( \frac{1}{\omega_r} \right) \tan^{-1} \left[ \cot(\omega_r(t_1 - t_0)) \right] \quad (2) $$

By the completion of this mode, the voltage across main switch goes to zero and favorable conditions for ZVS turn on of $S_M$ will prevail.

Mode III ($t_2 - t_3$):
Initial conditions:
\[ v_C(0) = 0, i_{D_A}(0) = I_g, i_{r}(0) = I_g - \frac{V_0}{Z_r}[\sin(\omega_r(t_2 - t_1) - \omega_r(t_1 - t_0))] \]

During this mode, resonating capacitor starts charging and main inductor current equation obtained is,
\[ i_{LM}(t^1) = I_g - \frac{2V_0}{Z_r}[\sin(\omega_r(t_2 - t_1) - \omega_r(t_1 - t_0))] \] (3)

**Mode IV (t_3 - t_4):**
Resonating capacitor (C_r) charges to its full value before this mode. During this mode, \( i_L = i_{LM} \), main inductor (I_{LM}) charges linearly through a steady source current (I_g).

**Mode V (t_4 - t_5):**
In this mode, main switch is switched OFF in hard-switching condition.

**Mode VI (t_5 - t_6):**
This duration is equivalent to free-wheeling interval of traditional boost converter.

**Mode VII (t_6 - t_7):**
The time domain equation of this mode is,
\[ t_7 = I_g \frac{(i_L + i_M)}{V_0} \] (4)

**Mode VIII (t_7 - t_8):**
In this interval, a steady-state current equal to I_g flows through the main switch and this interval exists till the firing of auxiliary switch.
\[ t_8 = (D-D_{sa})T_s \] (5)

**Mode IX (t_8 - t_9):**
This mode begins with the switching ON of auxiliary switch and the time domain equation is given by \( t_9 \), Initial conditions:
\[ \begin{align*} i_{LM}(0) &= I_g, v_{C_r}(0) = V_0, i_{r}(0) &= 0 \\ t_9 &= t_8 + \frac{\pi}{2} \sqrt{L_r C_r} \end{align*} \] (6)

**Mode X (t_9 - t_{10}):**
Initial conditions:
\[ \begin{align*} i_{LM}(0) &= I_g, v_{C_r}(0) = 0, i_{r}(0) &= \frac{V_0}{Z_r}, v_{L_2}(0) &= 0, \end{align*} \]
and the time domain equation of this mode is,
\[ t_{10} = t_9 + \left| \frac{1}{\omega_o} \right| \cos^{-1} \left[ \frac{-I_g \omega_o L_M \sqrt{1 + T_2 / T_M}}{V_0 \omega_o (\omega_o t_2 - \omega_o t_1)} + 1 \right] \] (7)

**Mode XI (t_{10} - t_{11}):**
The time domain equation of this mode is,
\[ t_{11} = t_9 + \left| \frac{1}{\omega_o} \right| \left[ \pi + \cos^{-1} \left( -1 + \frac{\omega_o \sqrt{1 + T_2 / T_M}}{\omega_o \sin(\omega_o (t_2 - t_1))} \right) \right] \] (8)

**Mode XII (t_{11} - t_{12}):**
During this mode, the main diode voltage will be decreasing as the resonating capacitor is charging.
\[ t_{12} = t_{11} + \left| C_r \right| \left( V_0 - V_0 \frac{\sin(\omega_r (t_{12} - t_0)) [\sin(\omega_r (t_{11} - t_{10}))]}{I_g \sqrt{1 + T_2 / T_M}} \right) \] (9)

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Mode XIII \((t_{12} - t_{13})\):
In this interval, main diode current reaches a steady-state value and this interval prevails till the main switch is turned ON at \(t_{13} = T_s\).

3. GATING SEQUENCE AND DESIGN OF POWER STAGE COMPONENTS

Gating sequence requirement in case of improved ZVZCT scheme is presented in Figure 5. According to the discussion, the modified scheme offers certain advantages for execution of IZVZCT operation. In this the switching pattern is synchronized such that it helps in real time implementation. In case of normal ZVZCT operation, the first pulse of \(S_A\), in which the ascending side of main switch gating signal must be matched with descending side of the auxiliary switch gating pulse, this pulse is called ZVS pulse for auxiliary switch and the second pulse of \(S_A\), in which the descending side of \(S_A\) and \(S_A\) gate pulses should coincide (should be withdrawn simultaneously). This pulse is called ZCT pulse for the auxiliary switch.

In the modified version of ZVZCT operation, even after \(S_M\) is switched ON, the gate pulse of \(S_A\) is to be continued for some extended time, to achieve the soft-switching. This is called time delay 1 which starts between the starting of the gating pulse for main switch and the instant of withdrawing the gating pulse to auxiliary switch. Similarly, even after the \(S_M\) is switched OFF, the gate pulse of \(S_A\) is to be continued for some extended time, in order to achieve the soft-switching and this is called time delay 2 between the instant of withdrawal of the gate pulse for \(S_M\) and the instant of withdrawing the gate pulse to \(S_A\).

On observing the gate pulse requirement needed for the auxiliary switch for both ZVT and ZCT operations, it has been thought to apply the combination of both pulses as depicted in Figure 5. Here, the auxiliary switch will be switched twice as compared to the main switch in a given switching cycle. In other words, the switching frequency of \(S_A\) will be twice that of \(S_M\). The design parameters of the converter are given below in Table 2.

![Figure 5. Gating sequence requirement in IZVZCT scheme](image)

| Parameters | Design values |
|------------|--------------|
| Power output \((P_i)\) | 30 W |
| Output voltage \((V_o)\) | 24 V |
| Switching frequency \((f_s)\) | 100 kHz |
| Input inductor 1 \((L_i)\) | 120 µH |
| Input inductor 2 \((L_i)\) | 25 µH |
| Main inductor \((L_m)\) | 0.7 µH |
| Load capacitor 1 \((C_l)\) | 200 µF |
| Load capacitor 2 \((C_l)\) | 52 µF |
| Resonance inductor \((L_r)\) | 0.5 µH |
| Resonance capacitor \((C_r)\) | 200 nF |

3.1. Necessary and sufficient conditions for IZVZCT operation

In order to achieve IZVZCT operation, the necessary and sufficient conditions will be same as that of ZVZCT modes of operation. In other words, the duration of the auxiliary switch pulse during ZVT and ZCT cannot be the same. If they are same, for the positive variation of the loads, the violation of the ZCT soft-switching happens although ZVT may be still satisfying. Here, the input and output operating conditions are set such that ZCT is satisfied over wide range. If the converter satisfies the ZCT then ZVT is automatically ensured but vice-versa is not true. In such case, certain operating conditions may satisfy the ZVT while violating the ZCT conditions. The above information is due to the design of the converter. Basically, it is done for achieving ZCT and by employing suitable gating sequence ZVT and IZVZCT operations can also be achieved. On observing the necessary and sufficient conditions for both the operations, the duration of ZVT pulse requirement is lesser than the duration of ZCT pulse. In other words, for the same ZVT and ZCT pulses of the auxiliary switch, the margin in achieving ZVT is more as compared to ZCT for positive load changes.

4. DESIGN OF VOLTAGE-MODE CONTROLLER

As, this higher-order converter is experiencing different topological variations over one switching cycle. Due to this, it is a challenging task to achieve the transfer function of the system by state-space
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approach. Hence, by employing system identification tool and by P & O method, the system transfer function is obtained for IZVZCT operation with suitable interval (greater than 85%). Implementation of analog controllers are already existing and now-a-days digital controllers are more focused because of their added merits such as lesser sensitivity to noise, greater sensitivity to changes in parameters and less vulnerability to aging and environmental issues.

Among different control techniques, the voltage-mode scheme is better and highly effective. Further, it provides good dynamic response and also there is no stability problems. Thus, a digital voltage-mode controller is employed for the modified ZVZCT converter. The transfer function of the plant \( G_p(z) \) for IZVZCT operation has been obtained with the help of system identification tool and this is given in equation 10. Output Error (OE) method has been adapted and for a best fit of 88.9\%, the transfer function obtained is

\[
\frac{v_d(z)}{d(z)} = \frac{-0.003134z^3 + 0.1271z^2 - 0.1556z + 0.005982}{z^4 - 3.838z^3 + 5.519z^2 - 3.525z + 0.8434}
\]  

(10)

The voltage-mode controller is designed considering the above transfer function of open loop system is,

\[
G_c(z) = 0.10635 \times \frac{(z-0.875)(z-0.961)}{(z-1)(z-0.912)}
\]  

(11)

Utilizing the transfer functions of plant \( G_p(z) \), compensator \( G_c(z) \), and loop gain is expressed as,

\[
T_L(z) = G_p(z) G_c(z)
\]  

(12)

Figure 6 depicts the closed loop block diagram of the converter. The GM, PM and BW values for the designed controller are achieved from the bode plots of the open loop transfer function of converter and also with controller implementation are shown in Figures 7 and 8.

Figure 6. Block diagram of closed loop system

Figure 7. Frequency response characteristics of IZVZCTBC
Figure 8 infers that, the GM is 10.5 dB, PM is 33.5° and the gain crossover frequency is 416 Hz, which are all satisfying stability criteria for the designed controller. The frequency response plots of the Converter (G_p(z)), Controller (G_c(z)) and Loop gain (T_L(z)) are shown in Figure 9.

Figure 8. PZ map and frequency response plot of IZVZCTBC

5. VALIDATION OF CONTROLLER PERFORMANCE FOR IZVZCT OPERATION

The designed digital controller has been verified for different input and output variations in simulation. Load variation of output resistance from 20 Ω to 36 Ω has been given and after 10 ms the voltage of the converter got regulated within 2 ms by the controller action. A sudden variation of 12 V to 15 V is applied to the source, which in turn made the transients to die down within 2 ms and also the performance of the controller was satisfactory and the matching results are depicted in Figure 10.

Ramp disturbance of 12 V to 15 V from 20 ms to 60 ms has been given as the input, in which it made the transients to die down within 2 ms and also the performance of controller is satisfactory. The corresponding results are shown in Figure 11.

Figure 10. Dynamic response characteristics of IZVZCTBC, (R = 20 - 36 Ω at t = 10 ms; V_g = 12 - 15 V at t = 20 ms)

Figure 11. Dynamic response characteristics of IZVZCTBC, (V_g = 12 - 15 V from 20 - 60 ms)
6. RESULTS AND DISCUSSION

As explained already, the peak in the main switch current during turn ON transition is present in the case of conventional ZVZCT networks and the relatively large negative peak in main switch current will be eliminated by incorporating the improved soft-switching cell under consideration into the converter. Figure 12 depicts the elimination of main switch current stress of IZVZCTBC.

![Figure 12. Elimination of main switch current stress](image)

Figures 13, 14, 15 and 16 depicts the voltage/current waveforms of main and auxiliary switch, main and auxiliary diode. From these Figure s, it can be concluded that along with main and auxiliary switches the L-C-S tank network is also capable of providing soft-transition conditions for main and auxiliary diodes, whereas in conventional ZVZCT networks it can be noticed that it is providing soft-switching conditions primarily for $S_M$ and is not addressing the hard-switching problem of other switching devices.

![Figure 13. Main switch voltage & current](image)

![Figure 14. Auxiliary switch voltage & current](image)

![Figure 15. Main diode voltage & current](image)

![Figure 16. Auxiliary diode voltage & current](image)

Theoretical losses and efficiency study for soft and hard-switched converters has been done and the results are depicted in Figure s 17 and 18. From the plots, it is clear that, at lighter loads, the efficiency of hard-switched converter is poor and increases for increasing loads. The efficiency will be maximum around nominal operating point, whereas in case of soft-switched converter, its light load efficiency is also better and is almost constant throughout the vast variation in load. The efficiency of hard-switched converter is about 89% at rated load and it is about 97% in case of soft-switched converter. The theoretical efficiencies of both hard and soft-switched converters have been plotted for the same rated load and examined that the soft-switched converter is resulted in improved efficiency of about 5 to 8%.

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7. CONCLUSION

An Improved Zero-Voltage Zero-Current Transition Boost Converter is introduced and its operational modes are described with time domain equations. The IZVZCTBC is the circuit modification of the traditional ZVZCT boost converter with extra auxiliary network elements and the converter topology is achieving ZVT, ZCT and IZVZCT for switching devices ($S_M$, $S_A$, $D_M$, $D_A$), by applying proper sequence of gating signals for main and auxiliary switches. The choice of proper resonance network components is very significant in obtaining soft-transition operation for the switches. The ZVT/ZCT conditions are dependent on duty ratio of gate pulses, soft-switching capacitance/inductor and load. The structural advantage of the L-C-S tank network under consideration with the boost converter together is examined for the chances of achieving ZVT, ZCT and IZVZCT by properly adjusting the gate sequence to the auxiliary switch. The above investigation has been done without changing the various elemental values and with the employment of the proper gate sequence for the switches is able to achieve the ZVT, ZCT and IZVZCT.

The system identification technique was described and converter transfer function was obtained for IZVZCT operation and its frequency response analysis is presented. The voltage-mode digital controller for the converter has been designed using MATLAB [25] and it is validated in PSIM [24] simulation platform. The controller designed is regulating the load voltage for variations in load and input supply. The GM, PM and BW of the controller are satisfying the stability criteria and the IZVZCT operation of the two switches have been achieved in the simulation. This converter is suitable for point of load applications with power levels in the kW range.

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