DESIGN, ANALYSIS AND CONTROL OF A QUASI-RESONANT LUO CONVERTER WITH A HIGH VOLTAGE GAIN

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Key words: Dc/dc converters, Soft switching, Zero current switching (ZCS), Transfer voltage gain, Sliding mode control (SMC).

In this paper, a zero current switching Luo converter has been presented. Here, a series resonant cell is integrated with a Luo converter and the required conditions are achieved for zero current commutation of the switch and zero voltage commutation of the diodes. The major advantages of this soft switching converter include its high voltage transfer gain, high efficiency and stress reduction of the switch and diodes. Moreover, analysis of the ZCS Luo converter in steady state region is performed and curves of voltage transfer gain of the converter are derived in different operating points. In order to improve the dynamic and static performances of the proposed converter, a proportional integral (PI) and sliding mode controller has been used. The performance of the converter under the proposed controller is verified using MATLAB software. The results show the excellent behavior of the proposed converter under the designed controller.

1. INTRODUCTION

In recent days, high efficiency and high power density is one of the important and challenging issues in energy and power sector [1–3]. In order to connect an energy source, such as solar photovoltaic (PV) cells, to a consumer end, power electronic systems are required. The solar PV cells are preferred for low power systems. These cells could not be used in high power applications, because of high losses and low efficiency [4, 5]. In order to enhance capability of such systems, a dc/dc converter with high voltage transfer gain and high efficiency is required. A dc/dc converter is capable to invert low voltage of the PV systems to a high voltage. Moreover, dc/dc converters with high voltage transfer gain are used in many of industrial applications such as microgrid systems, fuel cell systems, batteries, capacitor networks, power supplies, uninterruptible power source (UPS) systems and etc [6, 7]. Among dc/dc converters, voltage transfer gain of boost and buck-boost pulse width modulation (PWM) dc/dc converters is limited. Moreover, the efficiency of these converters decreases with the increment in voltage transfer gain, because of the conductivity losses and switching losses [8]. Also, isolated dc/dc could be used to increase voltage. However, non-isolated dc/dc converters are preferred for low power applications, because of their low cost, good power density and higher efficiency [9, 10]. Among non-isolated dc/dc converters, converters with coupled inductor are popular. These converters are capable to convert input voltage to output voltage with a higher voltage transfer gain as compared with boost and buck-boost dc/dc converters. Moreover, implementation of the control circuit of these dc/dc converters is simple. However, there is an undesirable voltage spike in the off-state of the switch of these converters, because of the leakage energy of their coupled inductors. In order to reduce this voltage spike, lossless passive clamp circuits are used [11, 12], leading to a high stress voltage on diodes. Therefore, efficiency of these dc/dc converters decreases.

In recent days, voltage lift dc/dc converters have been presented. These converters have a high voltage gain as compared with other conventional dc/dc converters [13]. In the voltage lifting (VL) method, the output voltage of dc/dc converters is increased in geometric progression. This method has been employed in conventional dc/dc converters. In the super lift technique, the output voltage of dc/dc converters is increased in geometric progression [14–18]. This method has been employed in design of POESLL and NOESLL converters and cascade boost converter [19–22]. The dc/dc converters presented in [13–22] possess a high voltage transfer gain as compared with other conventional dc/dc converters. However, switching losses of these converters are fairly large. The ultra-lift technique is a novel approach in the design of dc/dc converters. It produces a higher voltage transfer gain. The ultra-lift Luo converter has been designed using the ultra-lift Luo technique. This converter is capable to convert input voltage with positive polarity into output voltage with negative polarity. The ultra-lift Luo (ULL) converter is an attractive topology with a high voltage gain and simple structure. It has a small duty cycle in high voltage gain, high power density. These unique features make the ultra-lift Luo converter a superior candidate for power electronic systems [23]. On the other hand, at high frequencies, the ultra-lift Luo converter experience electromagnetic interference, reduced reliability and high switching losses. In order to overcome these problems, quasi resonant converters are used. High efficiency can be achieved by using quasi resonant converters, because commutation of switch and diodes of these converters take place in zero voltage switching and zero current switching conditions [24, 25]. Moreover, quasi resonant converters have the advantages of lightweight and smaller volume and high power density, because of low switching losses and high frequency. So far, many quasi resonant dc/dc converters have been presented. In [26], analysis of a series resonant soft switching dc/dc converter has been reported in discontinuous current mode. In [27], performance of a zero voltage soft switching buck dc/dc converter has been studied. In [28], a ZCS/ZVS boost dc/dc converter has been presented for dc microgrid. The dc/dc converters presented in [26–28] have a high efficiency and low switching losses along with a small voltage transfer gain which can restrict the converter performance. A hybrid resonant ZCS converter is suggested in [29], which uses several switches and diodes. Also, a new energy storage circuit is designed by using...

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multiple-switch stages in [30] and a input parallel output-series dc/dc topology is developed in [31], utilizing a shunt-connected resonant capacitor and transformer leakage inductance to achieve soft resonant current commutation. The main disadvantage of the converters reported in [29–31] is requirement to large numbers of active elements, resulting in the expense of more complicated control circuit.

In this paper, a zero current soft switching ultra-lift Luo (ZCS ULL) dc/dc converter has been presented. It has a major advantage of high voltage transfer gain as compared with other conventional soft switching dc/dc converters. In addition, soft switching method causes increment of efficiency and power density of the ultra-lift dc/dc converter. The ZCS ULL converter is shown in Fig. 1a. Here, a resonant tank is series with the switch of the ZCS ULL converter. Therefore, zero current switching condition of the switch of the converter is achieved. The zero current switching reduces switching losses in high frequencies. Moreover, zero voltage switching condition of the diodes of the converter could be achieved. The zero voltage switching reduces the reverse recovery losses of the diodes. Moreover, it removes the voltage spikes of the diodes during the ON and OFF times and eliminates the necessity of the snubber circuits. The proposed converter can be used in high voltage applications.

In order to improve the performance and efficiency of dc/dc converters, resonant switching techniques are used. The output voltage regulation of resonant converters is an important criterion in designing power systems. In order to achieve an excellent regulation and enhance the performance of resonant converters, a robust controller is required. Traditionally, the proportional integral derivative (PID) controllers have been presented for voltage regulation of resonant converters [32]. In [33], a PI and fuzzy logic controller has been presented for voltage regulation of a resonant boost converter. In [34, 35], an input-output linearization controller has been presented for voltage regulation of a series parallel resonant converter and a ZVS CLL-T resonant converter. However, in order to use these controllers, a complicated driver circuit is required. This circuit must be capable to turn off the switch of the resonant converter in ZCS/ZVS conditions. It increases the complexity, cost and size of the controller. These disadvantages can be overcome by using a PI and sliding mode controller. Design of sliding mode controllers has been discussed in [16, 36] for PWM dc/dc converters. The PI and SMC can drive the switch of the proposed converter at zero crossing instances of resonant inductor current without using zero current crossing detection circuit. Thus, the aforementioned drawbacks could be eliminated.

This paper focuses on the design and analysis of a ZCS ULL converter in steady state region. Based on the aforementioned discussions, this study is organized as follows: In Section 2, circuit topology of the ZCS ULL converter is presented. In Section 3 the steady state performance of the converter is analyzed and equations of the state variables of the converter are presented. In Section 4, voltage transfer gain of the converter is obtained. In Section 5, simulation results are shown. Moreover, the efficiency curve voltage gain of the ZCS ULL converter is shown in different operating points. Finally, the conclusions have been given in Section 6.

2. THE PROPOSED CONVERTER

The ZCS ULL converter is shown in Fig. 1a. It is constituted of a power switch S, freewheeling diodes D1, D2, D3, two inductors L1, L2 and two capacitors C1 and C2. The inductor Lr and capacitor Cr are designed to construct a resonant circuit. In Fig. 1a, R and E are the load and input voltage, respectively. \(i_{Lr}\) and \(v_{Cr}\) represent the instant values of the resonant current and voltage, respectively. \(V_{C1}\) and \(V_{C2}\) are the average values of the inductor currents \(L_1, L_2\) and the capacitor voltages \(C_1, C_2\) in steady state.
region, respectively. It is supposed that the ZCS ULL converter operates in continuous conduction mode and all the components are ideal. Moreover, the values of the inductors $L_1$, $L_2$ and capacitors $C_1$ and $C_2$ are large enough.

Therefore, the average values of inductor currents $I_{L1}$, $I_{L2}$ and capacitor voltages $V_{C1}$ and $V_{C2}$ are constant in steady state region. The resonance between $L_r$ and $C_r$ shapes the switch current to become a quasi-sinusoidal waveform. It provides the conditions for zero current switching operation of the switch and zero voltage switching operation of the diodes of the proposed converter.

3. THE PERFORMANCE OF THE PROPOSED CONVERTER IN STEADY STATE REGION

The waveforms of the ZCS ULL converter are shown in Fig. 1b. The steady state performance of the converter is studied in five operating modes. The operating modes of the converter are shown in Fig. 2.

Mode 1 ($t_0 < t < t_1$): At the moment of $t_0$, the switch of the converter is conducting and the diode $D_3$ is turned off with ZVS. In this mode, the diodes $D_1$ and $D_2$ are in the off state. At this time interval, the inductor $L_r$ and capacitor $C_r$ participate in resonance. The inductor current $i_{Lr}$ increases from zero and the capacitor voltage $v_{Cr}$ increases from $-V_O$. The equivalent circuit of this operating mode is shown in Fig. 2a. $i_{Lr}(t)$ and $v_{Cr}(t)$ are given from the solution of the steady state differential equations of the converter as follows:

$$i_{Lr}(t) = I_{L2}(1 - \cos(w_d)) + Z_0(E + V_O)\sin(w_d), \quad (1)$$

$$v_{Cr}(t) = E - (E + V_O)\cos(w_d) - \frac{I_{L2}}{Z_0}\sin(w_d), \quad (2)$$

where

$$w_0 = \frac{1}{\sqrt{L_r C_r}}, \quad Z_0 = \frac{\sqrt{L_r}}{C_r}. \quad (3)$$

Mode 2 ($t_1 < t < t_2$): At the moment of $t_1$, the voltage of the resonance capacitor $v_{Cr}$ equals to $-V_C$. At this time, the diode voltage $v_{D1}$ becomes zero and the diode $D_2$ turns off with ZVS. Also, the diode $D_1$ conducts with ZVS. The equivalent circuit of this mode is shown in Fig. 2b. In this mode, the steady state differential equations of the converter are obtained as follows:

$$i_{Lr}(t) = I_{L1} - (I_{L1} - I_{L2}(t_1))\cos(w_d) + Z_0(E + V_C)\sin(w_d)$$

$$v_{Cr}(t) = E - (E + V_C)\cos(w_d) - \frac{I_{L1} + I_{L2}}{Z_0}\sin(w_d), \quad (3)$$

where

$$i_{Lr}(t_1) = I_{L2}(1 - \cos(w_0\Delta t)) + Z_0(E + V_O)\sin(w_0\Delta t_0) \quad (5)$$

$$\Delta t_1$$ can be obtained by using following relation:

$$-V_C = E - (E + V_O)\cos(w_0\Delta t_1) - \frac{I_{L2}}{Z_0}\sin(w_0\Delta t_1). \quad (6)$$

Mode 3 ($t_2 < t < t_3$): At the moment of $t_2$, the switch of the converter is turned off with ZCS. In this mode, the diode $D_1$ conducts and the voltage of the resonance capacitor $v_{Cr}$ increases linearly. The equivalent circuit of this mode is shown in Fig. 2c. In this mode, the steady state differential equations of the converter are obtained as follows:

$$v_{Cr}(t) = -\frac{1}{C_r}(I_{L1} + I_{L2})t + v_{Cr}(t_2), \quad (7)$$

where

$$v_{Cr}(t_2) = E - (E + V_C)\cos(w_0\Delta t_2) - \frac{I_{L1} + I_{L2}}{Z_0}\sin(w_0\Delta t_2) \quad (8)$$

$$\Delta t_2$$ can be given by solving the following equation:

$$0 = I_{L1} - (I_{L1} - i_{Lr}(t_1))\cos(\Delta t_2) + Z_0(E + V_O)\sin(w_0\Delta t_2). \quad (9)$$

Mode 4 ($t_3 < t < t_4$): At the moment of $t_3$, the voltage of the resonance capacitor $v_{Cr}$ equals to $-V_C$. Thus, the diode $D_1$ turns off with ZVS. Also, the diode $D_2$ conducts with ZVS. In this time interval, the capacitor voltage $v_{Cr}$
decreases linearly. The equivalent circuit of this mode is shown in Fig. 2d. In this mode, the steady state differential equations of the converter are obtained as follows:

$$v_{Cr} = -\frac{1}{C_r} I_{L2} t - V_{C1}.$$  \hspace{1cm} (10)

$$\Delta t_3$$ can be given by solving the following equation:

$$-V_{C1} = -\frac{1}{C_r} (I_{L1} + I_{L2}) \Delta t_3 + v_{Cr}(t_2)$$ \hspace{1cm} (11)

Mode 5 ($t_5 < t < t_6$): At the moment of $t_6$, the voltage of the resonance capacitor $v_{Cr}$ equals to $-V_o$. Thus, the diode $D_3$ turns on with ZVS. In this time interval, the capacitor voltage $v_{Cr}$ equals to $-V_o$. The equivalent circuit of this mode is shown in Fig. 2e. In this mode, the steady state differential equations of the converter are obtained as follows:

$$-V_o = -\frac{1}{C_r} I_{L2} \Delta t_4 - V_{C1}.$$ \hspace{1cm} (12)

### 4. VOLTAGE GAIN OF THE CONVERTER AND THE ZCS CONDITION

According to the operating modes of the ZCS ULL converter, it could be found that the output voltage increment could be performed by controlling the switching frequency and the time interval between $t_5$ and $t_6$.

$$\Delta t_5 = \frac{1}{f_s} - \Delta t_4 - \Delta t_3 - \Delta t_2 - \Delta t_1.$$ \hspace{1cm} (13)

The voltage transfer gain of the converter is obtained as:

$$M = \frac{V_o}{E}.$$ \hspace{1cm} (15)

where

$$f_0 = \frac{1}{2\pi \sqrt{L_r C_r}}.$$ \hspace{1cm} (16)

The normalized output current and switching frequency are defined as follows:

$$f_N = f_o,$$ \hspace{1cm} (17)

$$I_N = \frac{I_o Z_o}{E}.$$ \hspace{1cm} (18)

Moreover, in order to numerical solution of the above equations, the average values of the middle capacitor voltage $V_{C1}$ and the inductor currents $I_{L1}$, $I_{L2}$ must be calculated. The steady state waveform of these variables is shown in Fig. 3. In steady state region, the average values of the inductor voltage and capacitor current equal to zero. The instant values of the middle capacitor current $i_{C1}$, output capacitor current $i_{C2}$ and the inductor voltages $v_{L1}$ can be obtained as follows:

$$v_{L1} = \begin{cases} -V_{C1} & t_0 < t < t_1 \\ v_{Cr} & t_1 < t < t_3 \\ -V_{C1} & t_3 < t < t_5 \end{cases},$$ \hspace{1cm} (19)

$$i_{C1} = \begin{cases} I_{L1} - I_{L2} & t_0 < t < t_1 \\ -I_{L2} & t_1 < t < t_3 \\ I_{L1} - I_{L2} & t_3 < t < t_5 \end{cases},$$ \hspace{1cm} (20)

$$i_{C2} = \begin{cases} -I_O & t_0 < t < t_4 \\ -I_{L2} - I_O & t_4 < t < t_5 \end{cases}.$$ \hspace{1cm} (21)

By time averaging (19) to (21), the average values of the middle capacitor voltage $V_{C1}$ and the inductor currents $I_{L1}$, $I_{L2}$ can be given as:

$$\langle v_{L1} \rangle = -V_{C1} (\Delta t_1 + \Delta t_4 + \Delta t_5) + E \Delta t_5 - \frac{E + V_{C1}}{Z_o} \sin(w_0 \Delta t_5)$$

$$+ \frac{I_{L1} + I_{L2}}{Z_o} (\cos(w_0 \Delta t_3) - 1) - \frac{I_{L1} + I_{L2}}{2C_r} \Delta t_5^2 + v_{Cr}(t_2) \Delta t_5 = 0$$ \hspace{1cm} (22)

$$\langle i_{C1} \rangle = (I_{L1} - I_{L2}) (\Delta t_1 + \Delta t_4 + \Delta t_5) - I_{L2} (\Delta t_2 + \Delta t_3) = 0$$ \hspace{1cm} (23)

$$\langle i_{C2} \rangle = -I_O (\Delta t_1 + \Delta t_4 + \Delta t_5) + (I_{L1} - I_O) \Delta t_5 = 0$$ \hspace{1cm} (24)

Figure 1 shows the ZCS ULL converter and its waveforms. The condition for ZCS is expressed as follows:

$$0_p = \tan^{-1} \left( -\frac{Z_o (E + V_{C1})}{I_{L1} - i_{L2}(t_1)} \right),$$ \hspace{1cm} (25)

$$I_p = -|I_{L1} - i_{L2}(t)| \cos(w_0 t) + Z_o (E + V_{C1}) \sin(w_0 t).$$ \hspace{1cm} (26)

In order to satisfy (25), the following inequality must be satisfied:

$$I_p > I_{L1}$$ \hspace{1cm} (27)
5. SIMULATION RESULTS

In this section, the simulation results have been presented to show the dynamic and steady state performances of the ZCS ULL converter. Here, PSIM software has been used to simulate the system. The time step of the simulation control block of the PSIM was adjusted on 0.01 µs. The parameters of the converter are:

\[ L_1 = L_2 = 100 \, \mu H, \quad C_1 = C_2 = 100 \, \mu F, \quad L_r = 0.2 \, \mu H, \quad C_r = 0.4 \, \mu F, \quad R = 50 \, \Omega. \]

Due to step-down and step-up performance of the ZCS ULL converter, the voltage transfer gain of the converter is compared with a ZCS boost converter. Schematic of this converter is shown in Fig. 4. The transfer voltage gain of the ZCS ULL converter is obtained by numerical solution of the equations (1) to (14) and (22) to (24). These equations have been solved by using Matlab software. In different operating points, the voltage transfer gain of the ZCS ULL converter is compared with a ZCS boost converter.
ZCS ULL converter and the ZCS boost converter are shown in Figs. 5 and 6. From these figures, it could be found that the gain of the proposed converter significantly increases by increasing switching frequency of the converter. Moreover, it could be seen that the proposed ZCS ULL converter has higher voltage transfer gain as compared with ZCS boost converter.

In order to regulate the output voltage of the ZCS ULL converter without using zero current crossing detector circuit, a PI and SMC is presented, similar to the controller used in [32] and [33] for a Cuk converter and POESLCC. Figure 7 shows the connection of the controller and converter. Also, the photograph of the simulated circuit in PSIM software is shown in Fig. 8. The control objective is to enforce the output voltage to track a constant value under zero current switching condition of the switch of the converter. In Fig. 8, $v_d$ is a desire voltage, $v_o$ is the output voltage, $i_{L1}$ is the non-resonance inductor current. On other hand, the coefficients of the controller associated with the ZCS ULL converter were chosen as follows:

$$k_p = 0.1, \quad k_i = 8.5, \quad \delta = 0.1,$$

where $K_p$ and $K_i$ are the gains of the PI controller and $\delta$ is the hysteresis bandwidth of the controller. Figure 9 shows the transient behavior of the output voltage and the steady state response of $v_o$, $i_{L1}$ and $u$ for $E = 12$ V, $V_d = -36$ V and $R = 50$ Ω. From this figure, it be found that the switch of the converter is turned off and turned on in ZCS condition. This figure shows the proposed SMC can control the converter at ZCS conditions without using zero current crossing detection circuit.

Figure 10a shows the simulated responses of $v_o$ for $E = 12$ V, $V_d = -36$ V and $R = 25$ Ω at $t = 0.1$ s. Figure 10b shows the steady state responses of $v_o$, $i_{Lr}$ and $u$ for $E = 12$ V, $V_o = -36$ V and $R = 25$ Ω. From this figure, it is clear that the switch of the converter is turned off and turned on in ZCS condition.

Figure 11a illustrates the simulated responses of $v_o$ for $V_d = -36$ V and $R = 50$ Ω and input voltage variation from $E = 12$ V to $E = 18$ V at $t = 0.1$ s. Figure 11b shows the steady state responses of $v_o$ and $i_{Lr}$ for $E = 18$ V, $V_o = -36$ V and $R = 50$ Ω. From this figure, it is clear that the switch of the converter is turned off and turned on in ZCS conditions.

The efficiency of the proposed converter is shown in Fig. 12 for $Z_o = 1$ Ω and $F_o = 160$ kHz. It is clear that the efficiency of the converter decreases in low output currents.

6. CONCLUSIONS

This paper presents a quasi-resonant zero current switching ultra-lift Luo converter with a high voltage transfer gain. All the switch and diodes of the converter are subjected to very low current and voltage stress. The stress reduction of the switch and diodes reduces the switching losses and reverse recovery and increases the efficiency of the proposed converter. Due to the resonance performance of the converter, voltage spikes of the diodes of the converter eliminate. Hence, the diodes of the converter don’t require to snubber protection circuits. The sinusoidal analysis of the converter provides an overall understanding of the converter features.
In order to regulate the output voltage of the proposed converter, a PI and sliding mode controller has been developed. The SMC has a variable frequency structure and guarantees ZCS operation of the converter without using zero current crossing detection circuit. This method can be applied for controlling other resonant dc/dc converters with variable frequency structure.

Fig. 12 – The efficiency of the proposed converter for $Z_0 = 1 \, \Omega$ and $F_{OS} = 160 \, kHz$.

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