# A NEW SINGLE-PHASE Z-SOURCE CYCLOCONVERTER

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## Abstract

Single-phase cycloconverters are widely used for ac-ac power conversion especially for speed control of ac drives. In this paper, a new single-phase to single-phase Z-source cycloconverter topology is proposed. The proposed single-phase Z-source cycloconverter can boost to a desired voltage with various frequency. Thus, it is called a frequency step-down and amplitude voltage step-up converter. The operating principle of the proposed topology is presented. Analysis and simulation for this single-phase Z-source cycloconverter are also presented.

## 1. Introduction

The cycloconverters are used in high power applications such as variable frequency speed control for ac machines, constant frequency power supplies, controllable reactive power supply for an ac system, ac system interties and induction heating systems [1].

Recently, Z-source inverter is an innovative topology presented in [2]. It is a new type of converters besides the other two kinds of traditional converters: the voltage-source and the current-source converters. Its operating principle and applications for fuel cell inverters and adjustable speed drive (ASD) systems are illustrated in [3,4]. Considering the topologies of the Z-source converter, we observe that they could be directly extended or derived from the well-understood Z-source inverter topology. When used in ac-ac power conversion, the Z-source converter can provide higher output voltage than traditional PWM ac-ac converter advantageously. In addition, the simultaneous on or off state cannot destroy the devices.

In this paper, the Z-source concept employs to a single-phase cycloconverter to achieve both boosting amplitude and varying frequency of output voltage.

## 2. Proposed topology

Fig. 1 shows the proposed single-phase Z-source cycloconverter. It employs a Z-source network, bi-directional switches and RL load. All the inductors and capacitors are small and used to filter switching ripples. The symmetrical Z-source network, which is a combination of two inductors and two capacitors, is the energy strorage/filtering element for the Z-source ac-ac converter. Since the switching frequency is much higher than the ac source (or line) frequency, the inductor and capacitor requirement should be low [5]. The proposed single-phase Z-source cycloconverter requires four bi-directional switches $S_{ij}$ (i = 1, 2, 3, 4 and j = a, b) capable of blocking voltage and conducting current in both directions and one bi-directional source switch ($S_s$) to isolate the Z-source network and load from the source. The bi-directional switches are implemented with two diodes and two insulated gate bipolar transistors (IGBTs) connected in anti-parallel. The diodes are included to provide the reverse blocking capability. The IGBTs were used due to its high switching capabilities and high current carrying capacities desirable for high-power applications.

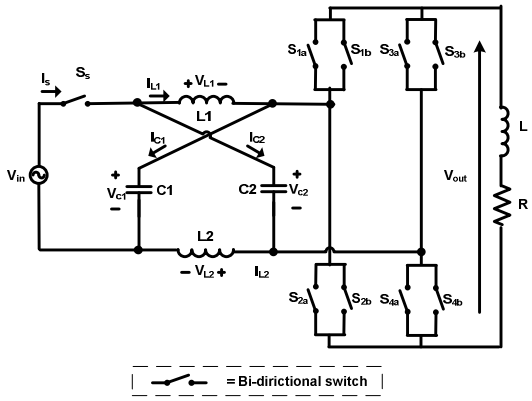


Fig. 1 Proposed single-phase Z-source cycloconverter

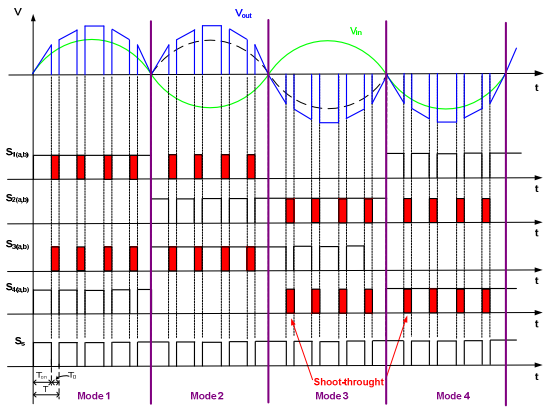


Fig. 2 Switching strategies for proposed topology

Fig. 2 shows the switching strategies for proposed single-phase Z-source cycloconverter. In this work the frequency of output voltage ($f_{out}$ = 30 Hz) is twofold less than that of input voltage ($f_s$ = 60 Hz). As shown in Fig. 2, $T_{on}$ and $T_0$ are an interval of an active state and a shoot-through state during the switching period, T, respectively.

The operation of the proposed single-phase Z-source cycloconverter can be divided into four modes as shown in Figs. 3 ~ 6. Mode 1: (Both input voltage and output voltage are positive). In active state, as shown in Fig. 3a, only three switches $S_s$, $S_{1a}$ and $S_{4a}$ are turned on; the ac source charges the Z-source network capacitors, while the inductors discharge and transfer energy to the load. In shoot-through state, as shown in Fig. 3b, only two switches $S_{1a}$, $S_{3b}$ are turned on; the Z-source network discharge, while the inductors charge and store energy.

Mode 2: (The input voltage is negative; the output voltage is positive). In active state, as shown in Fig. 4a, only three switches $S_{3a}$, $S_{2a}$ and $S_s$ are turned on; the ac source charges the Z-source network capacitors, while the inductors discharge and transfer energy to the load. In shoot-through state, as shown in Fig. 4b, only two switches $S_{3a}$, $S_{1b}$ are turned on; the Z-source network discharge, while the inductors charge and store energy.

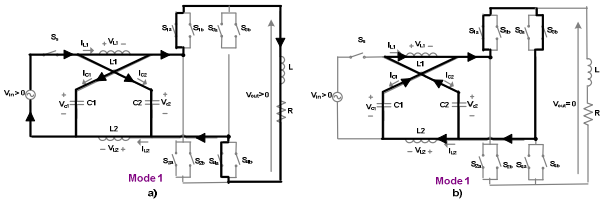


Fig. 3 Mode 1 – a) active state; b) shoot-through state

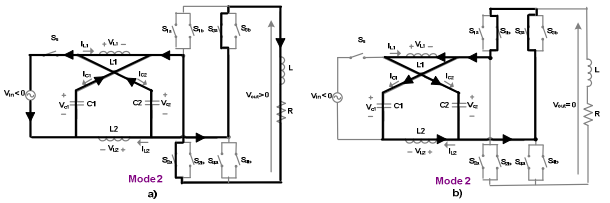


Fig. 4 Mode 2 – a) active state; b) shoot-through state

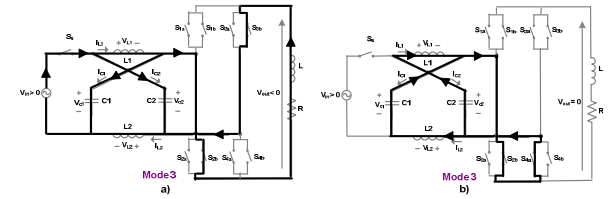


Fig. 5 Mode 3 – a) active state; b) shoot-through state

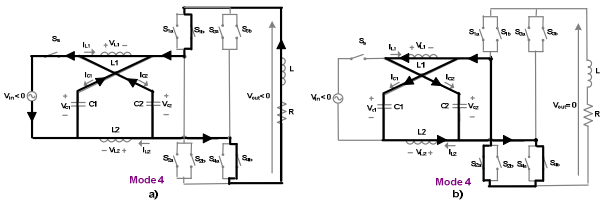


Fig. 6 Mode 4 – a) active state; b) shoot-through state

Mode 3: (The input voltage is positive; the output voltage is negative). In active state, as shown in Fig. 5a, only three switches $S_s$, $S_{2b}$ and $S_{3b}$ are turned on; the ac source charges the Z-source network capacitors, while the inductors discharge and transfer energy to the load. In shoot-through state, as shown in Fig. 5b, only two switches $S_{2b}$, $S_{4a}$ are turned on; the Z-source network discharge, while the inductors charge and store energy.

Table 1: Sequence of switching control

| *Input frequency* | *Output frequency* | *Mode* | *Switch "on" states* | |
|---|---|---|---|---|
| | | | Active state | Shoot-through state |
| 60 Hz | 30 Hz | 1 | $S_s$, $S_{1a}$, $S_{4a}$ | $S_{1a}$, $S_{3b}$ |
| | | 2 | $S_{3a}$, $S_{2a}$, $S_s$ | $S_{3a}$, $S_{1b}$ |
| | | 3 | $S_s$, $S_{2b}$, $S_{3b}$ | $S_{2b}$, $S_{4a}$ |
| | | 4 | $S_{4b}$, $S_{1b}$, $S_s$ | $S_{4b}$, $S_{2a}$ |

Mode 4: (The input voltage is negative; the output voltage is negative). In active state, as shown in Fig. 6a, only three switches $S_{4b}$, $S_{1b}$ and $S_s$ are turned on; the ac source charges the Z-source network capacitors, while the inductors discharge and transfer energy to the load. In shoot-through state, as shown in Fig. 6b, only two switches $S_{4b}$, $S_{2a}$ are turned on; the Z-source network discharge, while the inductors charge and store energy. In summary, the operation of modes is given in table 1.

The converter has two operating states: active stave and shoot-through state. Fig. 3a and 3b show the equivalent circuits for these two stages. The input voltage is

$$v_s = V_i \sin(2\pi f_i t) \quad (1)$$

Assume that the inductors $L_1$, $L_2$ and capacitors $C_1$, $C_2$ have the same inductance (L) and capacitance (C), respectively, the Z-source network becomes symmetrical. Then we have

$$v_{L1} = v_{L2} = v_L = V_L \sin(2\pi f_i t + \theta_L) \quad (2)$$

$$v_{C1} = v_{C2} = v_C = V_C \sin(2\pi f_i t + \theta_C) \quad (3)$$

And the output voltage is

$$v_{out} = V_0 \sin(2\pi f_o t + \theta_0) \quad (4)$$

where $\theta_L$ , $\theta_C$ , $\theta_0$ are phase angles of Z-source inductor voltage, Z-source capacitor voltage and output voltage, respectively.

In the active state ($T_{on}$), which shows in Fig. 3a, we have

$$v_C = v_{in} - v_L \text{ and } v_{out} = v_{in} - 2v_L \quad (5)$$

In the shoot-through state ($T_0$), which shows in Fig. 5b, we have

$$v_C = v_L \text{ and } v_{out} = 0 \quad (6)$$

In one fundamental period, the average voltage across the inductors should be zero. Thus, from (5) and (6) the capacitor voltage can be derived as

$$V_C = \left|\frac{T_{on}}{T_{on} - T_0}\right| V_{in} = \left|\frac{1 - D_0}{1 - 2D_0}\right| V_{in} \quad (7)$$

when $D_0 < 0.5$, $\theta_C = 0$
when $D_0 > 0.5$, $\theta_C = \pi$

where

$T = T_{on} + T_0$ : switching period

$D_0 = T_0 / T$ : shoot-through duty ratio

The peak of output voltage which is equivalent to the input voltage of the cycloconverter, can be expressed as

$$\hat{V}_{out} = V_C - V_L = \left|\frac{1}{1 - 2D_0}\right| V_{in} \quad (8)$$

when $D_0 < 0.5$, $\theta_C = 0$
when $D_0 > 0.5$, $\theta_C = \pi$

The capacitor voltage gain ($K_c$) and the output voltage gain ($K_0$) can be defined as

$$K_c = \frac{v_C}{v_{in}} = \frac{1 - D_0}{1 - 2D_0} \quad and \quad K_o = \frac{v_{out}}{v_{in}} = \frac{1}{1 - 2D_0} \quad (9)$$

## 3. Simulation Results

Simulations have been performed to confirm the analysis above with the configuration shown in Fig. 1. Parameters used are shown in table 2.

Table 2: Simulation Parameters

| *Input voltage ($V_{in}$)* | *220Vrms / 60Hz* | |
|---|---|---|
| Z-source network | Inductor ($L_1$=$L_2$) | 0.5 mH |
| | Capacitor ($C_1$=$C_2$) | 10 μF |
| Switching frequency ($f_{sw}$) | 10 kHz | |
| RL Load | R | 7 Ω |
| | L | 3 mH |

Fig. 7 and Fig. 8 show the simulation results of the input voltage, output voltage, capacitor voltage and output current with

shoot-through duty ratio $D_0 = 0.3$. The simulation results show that the capacitor voltage and the output voltage were boosted to $V_{C2}$ = 530V peak and $V_{out}$ = 750V peak from 220V rms or 311V peak input voltage. In addition, the frequency of output voltage is 30 Hz less than that of input voltage (60 Hz). On the other hand, the output voltage can be controlled to boost the amplitude and step-down frequency. It is clear that, as expected, the proposed single-phase Z-source cycloconverter is a frequency step-down and amplitude voltage step-up converter.

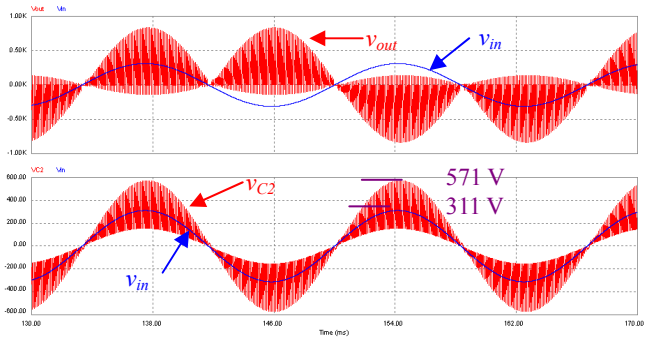


Fig. 7 Waveforms of the input voltage, output voltage (top) and input voltage, capacitor voltage (bottom) with shoot-through duty ratio $D_0 = 0.3$.

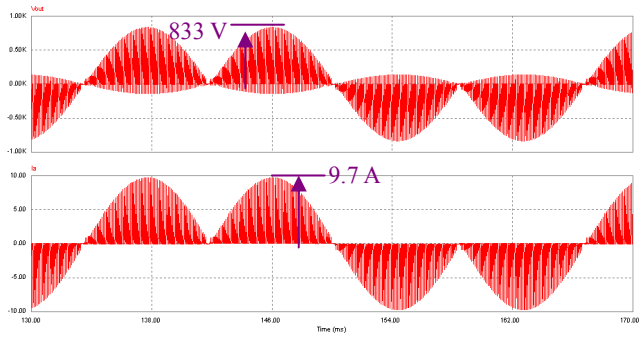


Fig. 8 Waveforms of the output voltage (top) and output current (bottom) with shoot-through duty ratio D0 = 0.3.

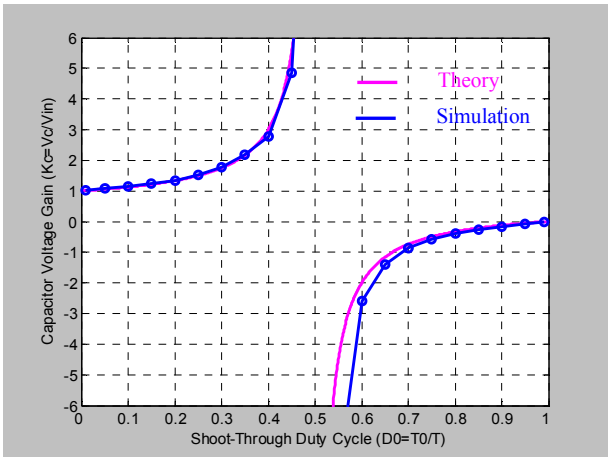


Fig. 9 Relationship between capacitor voltage gain and shoot-through duty cycle

Fig. 9 and 10 show the relationship between the capacitor voltage gain and the shoot-through duty cycle and the relationship between the output voltage gain and the shoot-through duty cycle, respectively. The calculated curves from simulation result are the same as the curves from analytical theory (see equation (9)). As shown in Fig. 10, there are two operating regions. When the shoot-through duty cycle is less than 0.5, the output voltage is in-phase with the input voltage. When the shoot-through duty cycle is greater than 0.5, the converter enters negative gain region, the output voltage is 180° out-of-phase with the input voltage.

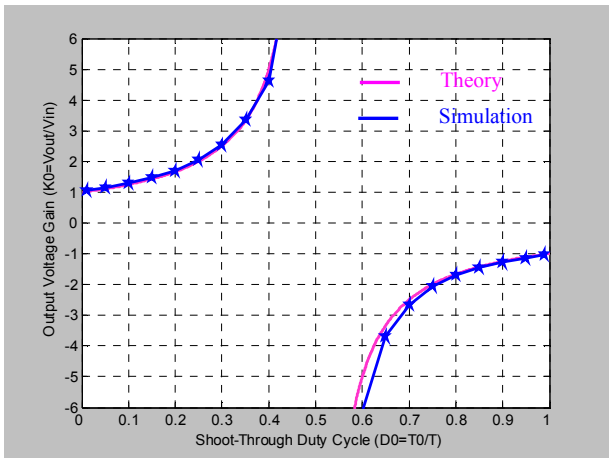


Fig. 10 Relationship between output voltage gain and shoot-through duty cycle

## 4. Conclusions

In this paper, a new single-phase to single-phase Z-source cycloconverter was proposed. The proposed single-phase Z-source cycloconverter can boost to a desired output voltage and change output frequency to a required value. Thus, the converter is a frequency step-down and amplitude voltage step-up converter. Based on the operating principle and theoretical analysis, a good simulation results are presented.

## 5. Acknowledgments

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