A Three-Phase AC-AC Buck-Boost Converter using Impedance Network

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Abstract: Impedance converters have been developed as a new type of converter besides the two other existing converters: voltage-source and current source converters. The new converter has many inherent advantages which can be used for many applications such as wind power conversion system, fuel cell system or motor drive applications. Present research works are mostly focused on using Z-source network as a dc-link. In this paper, the new three phase ac-ac Z-source converter buck boost capabilities are verified to perform ac-ac conversion directly. Mathematical analysis of the proposed converter verified by MATLAB simulation results is presented.

Key words: Zsi, Buck boost, Shoot through, Boost factor

I. INTRODUCTION

Impedance (z) source converters are introduced recently [1]. Z-source converters are proposed both for dc-ac and ac-ac conversions. For dc-ac conversion, a z-network of two inductors and two small capacitors connected between DC power source and the inverter bridge. It eliminates all the problems related to VSI and CSI and requires no extra switch. The network acts as a second-order filter to suppress voltage ripples more effectively than capacitor used in traditional PWM inverter and the inrush current and harmonics in the current can be reduced via the inductor [2]. Moreover the VSI based ZSI provides some special features that cannot be observed in the traditional inverter. It acts as a boost converter for dc-ac power conversion, desired ac voltage can be obtained, which is even greater than the source voltage. A short circuit across any phase leg is allowed, and so the provision of dead time is not necessary. However, in case of dc-ac z-source inverter(ZSI), depending of the topologies of impedance network, they are categorised as simple ZSI, Quasi ZSI, Trans Quasi ZSI and Trans ZSI. There are different switching techniques employing shoot-through pulses namely simple boost control (SBC), maximum boost control (MBC), maximum constant boost control (MCBC) etc. Again in case of ac-ac z-source converter proposed recently [3] has the capability to buck/boost the output voltage with minimal components. In single phase configuration it uses two inductors and two capacitors in a symmetric manner and in three phase ac-ac conversion it uses three inductors and three capacitors and can transfer the energy from ac to ac directly. It can overcome voltage sag or voltage surge in power system easily. Though it is suitable for variable voltage power source, it is not applicable in variable frequency power source. One advanced method using back-to-back converters is presented in [4],[5],[6]and [7].The converter used in those works is almost similar; differences lie in the control strategy. One option is to apply vector control to the supply-side converter, which is controlled to keep the DC-link voltage constant through regulation of the d-axis current. There is different circuit topologies developed for ac-ac converter used to approach to compensate for voltage conditioning. Pulse Width Modulation (PWM) control strategy are used for those topologies to take care voltage disturbances.[8] Show a topology of three phase ac-ac
converter using six bi-directional switched used with inductor and capacitor. Feed-forward switching technique with a DSP based control is applied here without discussing the details of it. The literature [9] explain the closed loop control of z-source converter for wind power application. A new family of simple topologies of three-phase ac–ac converters is proposed in [10] and [11]. In these topologies, the operating principle and control scheme are considered same as the corresponding dc–dc converters. A number of topologies are presented here in line with the dc–dc ones and they are buck, boost, buck-boost, Cuk and fly back converters. The proposed converters employ only two active devices reducing the cost and improving reliability. Bi-directional switches are used for switching purposes. A comparative evaluation of various such ac–ac converters capable of performing the power conditioning function are discussed in [11]. In a review paper [12], a number of possible topologies and outline of exemplary applications of single-phase ac–ac are presented. Examples of different application confirm interesting possibilities of ac-ac semiconductor transformers. In literature [13], several topologies for direct ac–ac converters like buck, full-bridge, half-bridge, and push–pull are discussed. These converters were used to implement a voltage restorer that can be supplied either on the line side or on the load side. For all the converters, their characteristics are summarized with static gain expressions, the transformer turns ratios, the current, and the voltage ripple across the converter output filter. Paper [14] present a new type of voltage regulator based on Z-Source converter that compensates wide range voltage fluctuations. Another literature [15] presents a novel PWM buck–boost ac chopper using regenerative dc snubbers. Proper switching operation for solving the commutation problem is utilized and the high-frequency PWM technique to control the output voltage is used to make it more reliable. It is claimed to have advantages like improved power factor, low harmonics, sinusoidal input current, fast dynamics, high reliability, efficiency, and significant reduction of the filter size. Those literatures mostly discuss the possible topologies and the detailed operating performance is not touched upon. In authors’ opinion, ac-ac semiconductor transformer applications will emerge in the near feature. Again, in line with the z-source inverter, inclusion of z-network in ac-ac converter is proposed for a single phase ac system by researchers in [16].

II. EQUIVALENT CIRCUIT, OPERATING PRINCIPLE OF THE PROPOSED THREE-PHASE AC-AC CONVERTER

The proposed converter uses impedance network as energy storing and releasing component. The circuit is shown in Figure 1 consisting of three inductors and three capacitors. The switches used are bidirectional in nature.

![Figure 1. Three phase ac-ac converter](image_url)
Figure 2. Three phase ac-ac converter equivalent circuit in non shoot through state.

Figure 3. Three phase ac-ac converter equivalent circuit in shoot through state

The Input line Voltages to the converter-

\[
\begin{align*}
V_{ab} &= V_i e^{i\frac{2\pi}{3}} \\
V_{bc} &= V_i e^{-i\frac{2\pi}{3}} \\
V_{ca} &= V_i e^{-i\frac{2\pi}{3}}
\end{align*}
\]

Equation 1

Corresponding Output line Voltages are-

\[
\begin{align*}
V_{a'b'} &= V_o e^{i\frac{2\pi}{3}} \\
V_{b'c'} &= V_o e^{-i\frac{2\pi}{3}} \\
V_{c'a'} &= V_o e^{-i\frac{2\pi}{3}}
\end{align*}
\]

Equation 2

Voltage across Inductors-
\[
\begin{align*}
\left( \frac{V_{L1}}{V_{L2}} \right) &= \left( \frac{V_{Le} e^{i0}}{V_{Le} e^{-\frac{2\pi}{3}}} \right) \\
\left( \frac{V_{L3}}{V_{L4}} \right) &= \left( \frac{V_{Le} e^{-\frac{2\pi}{3}}}{V_{Le} e^{i0}} \right)
\end{align*}
\]
Equation 3

Voltage across Capacitors-
\[
\begin{align*}
\left( \frac{V_{C1}}{V_{C2}} \right) &= \left( \frac{V_{Ce} e^{i0}}{V_{Ce} e^{-\frac{2\pi}{3}}} \right) \\
\left( \frac{V_{C3}}{V_{C4}} \right) &= \left( \frac{V_{Ce} e^{-\frac{2\pi}{3}}}{V_{Ce} e^{i0}} \right)
\end{align*}
\]
Equation 4

There exists two states shoot through and non shoot through state as shown in Figure 2 and Figure 3 respectively. During non shoot through period (1-D)T the switches S_{ap}, S_{bp}, and S_{cp} are kept on while the switches S_{an}, S_{bn}, S_{cn} are off. In shoot through period DT the switches S_{ap}, S_{bp}, and S_{cp} are kept off while the switches S_{an}, S_{bn}, S_{cn} are on.

Therefore, \( V_{L1} = V_{C3} - V_{ca} \)

\[ V_{L1} = V_{C1} \quad \text{Equation 5} \]

Averaging the voltage across inductor \( L_1 \) over one ac line period in steady state. We have

\[
V_c = \frac{3D-1}{2} + \frac{1}{2} \sqrt{3}(1-D) = V_c(1-D)(-\frac{1}{2} + \frac{1}{2} \sqrt{3})
\]
Equation 7

\[
\frac{V_c}{V_i} = \frac{(1-D)}{\sqrt{3D^2-3D+1}}
\]
Equation 8

Assuming filter and Z-source network inductances are very small and can be neglected. If the line frequency voltage drop across the inductor are neglected then the output line to line voltage can be approximated to \( V_c \).

Gain \( G = \frac{V_o}{V_i} = \frac{(1-D)}{\sqrt{3D^2-3D+1}} \)

Equation 9

Evidently, by controlling the duty cycle D, the output voltage of the converter can be bucked or boosted.

![Figure 4. Gain vs duty cycle plot](image)

Figure 4 represents the gain vs duty cycle plot. It is observed that there are two regions for gain greater than and less than one. The topology shown in Figure 1 can be used for boost mode in duty
cycle range between 0 and 0.5 and in buck mode between 0.5 and 1. Voltage gain is unity in case of D=0.5. In this proposed converter, there is a limit of maximum boost factor which is about 1.15 at D = 0.33. The voltage transfer ratio is estimated as

$$\frac{1-D}{\sqrt{2D^2-2D+1}}$$

III. SIMULATION AND EXPERIMENTAL RESULTS

To verify the working principle of the proposed converter simulations have been carried out in MATLAB environment. In order to clearly obtain fundamental component from the ac-ac converter an LC filter with 96Hz cut off frequency is inserted between converter and the load. The simulation parameters are chosen as 500μH and 10μF for the Z-source network and 10 KW R-L load. The switching frequency is set as 20 kHz. Figure 7 represents the steady balanced line voltage of 300v rms. The corresponding output voltage of the waveform without filter is shown in Figure 8.Upon FFT analysis of the boosted output voltage the THD is found to be 193.9% as shown in Figure 9. To filter out the harmonics inductors and capacitors of 55 mH and 50μF are connected across the output in buck mode, the corresponding filtered output voltage is shown in Figure 10. The filtered output FFT analysis is represented in Figure 11 and THD obtained is below 5%. For the boost mode of converter the output voltage waveform with filter parameters 35mH and 100μF is shown in Figure 5. The filtered output FFT analysis is presented in Figure 6 and THD obtained is below 5%. From the experimental results, the proposed ac-ac converter has a transfer ratio between 0 and 1.15. The maximum boost point is 1.15. The output waveforms shown is taken at duty cycle 0.38. From duty cycle range 0.38 to 0.5 the converter operates in buck mode with filter parameters 55mH and 50μF and operates in boost mode with filter parameters 35mH and 100μF.

![Figure 7. Three phase balanced input voltage](image1)

![Figure 8. Output line voltage of the inverter without filter](image2)
Figure 9. FFT analysis of the output voltage without filter

Figure 10. Output line voltage with filter

Figure 11. FFT analysis of the output voltage with filter

Figure 12. Output voltage in boost mode
IV. CONCLUSION

The z-source converter employs a unique impedance network to couple the converter main circuit to the power source, thus providing the unique features that cannot be observed in the traditional voltage source and current source converters where only one capacitor or inductor are used, respectively. The Z-source concept can be applied to almost all dc-ac, ac-dc, ac-ac and dc-dc power conversions. This paper is primarily focused on ac-ac conversion. Based on the theoretical analysis, simulation results are presented. The proposed three-phase ac-ac Z-source converter can keep the output voltage steady by operating at buck or boost mode. Therefore it has the capability to overcome the voltage sag or voltage surge which may damage the equipment.

V. REFERENCES


