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Hysteresis Band Current Control for a Single Phase Z-source Inverter with Symmetrical and Asymmetrical Z-network

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Abstract- A Z-source inverter has been proposed as a new topology in recent years. In this inverter an impedance network is placed between an inverter and a power source which provides both voltage buck and boost capabilities. This paper presents a unipolar hysteresis band current control method for a single phase Z-source inverter with symmetrical and asymmetrical Z-network configuration. The obtainable output current of this method in magnitude is higher than the hysteresis current control used in a traditional inverter. This paper also analyses the performance of the proposed control method under input dc voltage fluctuation and load current transient. Theoretical analysis and MATLAB simulations have been performed to describe and validate the control method.

Keywords—Asymmetrical Z-network, Hysteresis band current control, shoot through, Z-source inverter

I. INTRODUCTION

Traditional Voltage Source Inverter (VSI) and Current Source Inverter (CSI) are either a boost or a buck converter and are not a buck-boost converter. Recently, a Z-source inverter (ZSI) has been presented as a new topology of power electronic converters. It is a buck-boost converter that has a wide range of obtainable output voltage which traditional VSI and CSI inverters can not provide such features [2].

General representation of the Z-source inverter is shown in Fig.1-a where an impedance network is placed between a converter and a power source. A two-port impedance network which consists of inductors (L1 and L2) and capacitors (C1 and C2) connected in a special configuration to provide an impedance source (Z-source) which couples the converter to the power source. The unique feature of the Z-source inverter is that its output voltage can theoretically be changed between zero and infinite. The main circuit of the Z-source inverter and its operating principle have been described in [2]. Dynamic and transient performances of the Z-source inverter with symmetrical and asymmetrical networks are presented in [3,4]. A comparison between three types of inverters: traditional PWM inverter, dc/dc boosted PWM inverter and Z-source inverter for fuel cell vehicles are investigated in [6]. The control methods, to obtain a maximum voltage gain and to minimize the voltage stress across the inverter for any desired voltage gain have been described in [8, 9]. An application of the Z-source inverter for adjustable speed drives (ASD) by controlling the boost factor is presented in [10].

Fig.1-b shows a topology of the single phase Z-source inverter where the impedance network is placed between the power source and the single phase inverter.

As shown in table. 1, a single phase Z-source inverter has five possible switching states: two active states (vectors) when the dc voltage is connected across the load, two zero states (vectors) when the load terminals are shorted through either the lower or the upper two switches and one shoot through state (vector) when the

![Figure 1](image)
load terminals are shorted through both the upper and the lower switches of any one leg or two legs. These switching states and their combinations introduce a new PWM method for the Z-source inverter [2, 7, 12].

Fig. 2 shows the operating states of the single phase Z-source inverter in shoot through states that two switches of one phase leg or two phase legs are turned on simultaneously.

\[ V_i = \frac{T_0}{T} \cdot \left( 2V_c - V_d \right) = \frac{T_1 - T_0}{T_1 - T_0} V_d \]  

By applying \( T_1 = T - T_0 \) in Eq.5:

\[ V_i = \frac{1 - T_0}{T} V_d = \frac{1 - D_0}{1 - 2D_0} V_d \]  

Where \( D_0 \) is the shoot through duty cycle and \( V_d \) is the input voltage source.

Due to tolerance in capacitors and inductors, the Z-network configuration becomes asymmetric. In this paper maximum tolerances of the capacitors and inductors are defined as \( \pm 20\% \) and in a worst case, the Z-source impedance has \( C_1=1.2C, C_2=0.8C \) and \( L_1=1.2L, L_2=0.8L \). This shows an asymmetrical configuration of the Z-source inverter which has been analyzed in two sections. This paper presents a hysteresis current control for a single phase Z-source inverter with symmetrical and asymmetrical Z-network configuration based on unipolar modulation technique to generate a sine wave load current.

II. HYSTERESIS CURRENT CONTROL FOR A SINGLE PHASE TRADITIONAL INVERTER

A hysteresis current control technique is implemented with a closed loop system where an error signal, \( e(t) \), is used to determine the switching states and to control the load current. \( e(t) \) is a difference between the reference current, \( i_{ref} \), and the load current, \( i_L \). Fig. 3 shows a single phase full bridge inverter where four switches are turned on and off based on a modulation pattern to generate bipolar or unipolar voltage waveforms.

There are bands above and under the reference current and when the error reaches to the upper (lower) limit, the current is forced to decrease (increase) [1, 8].

![Fig. 3 single phase full bridge inverter](image)

A. Hysteresis current control based on bipolar switching technique

In bipolar switching scheme, there are two bands and the controller turns on and off the switch pairs \((S_1, S_2) \) or \((S_2, S_3)\) at the same time to generate \(+V_d\) or \(-V_d\) at the
output of inverter. As shown in Fig. 4, for the bipolar hysteresis current control technique, e(t) is applied to a hysteresis controller to turn on and off the switch pairs (S1, S4 or S2, S3).

![Diagram](image)

**Fig. 4.** Bipolar hysteresis current control (a) switching signals (b) load current with lower and higher band

**B. Hysteresis current control based on unipolar switching technique**

There are four switching states in an unipolar modulation scheme and according to Fig. 5, in this method the switches are turned on and off to generate three voltage levels, +Vdc, -Vdc or 0. In this method, there are four current bands; the first upper and lower bands are used when the output voltage is changed between (+Vdc & 0) or (-Vdc or 0) and the second upper and lower bands are used to change the voltage level when the derivative of the load current is changed. As shown in Fig. 6, two hysteresis controllers are used in the unipolar switching scheme to achieve a proper switching state to control the load current.

![Diagram](image)

**Fig. 5.** Unipolar hysteresis current control (a) switching signals (b) load current with lower and higher bands

**III. UNIPOLAR HYSTERESIS CURRENT CONTROL FOR A SINGLE PHASE Z-SOURCE INVERTER**

According to Fig. 1, a maximum obtainable load current can be created up to \( \frac{V_{dc}}{R} \) (R is the load resistance) and for increasing the load current, it is needed to apply the shoot through states in modulation scheme in order to boost the output voltage. For this purpose, the shoot through duty cycle can be estimated from Eq. 6:

\[
D_s = \frac{T_s}{T} = \frac{V_r - V_d}{2V_r - V_d}
\]  

(7)

Where \( V_r \) is the average DC-link voltage which is needed to boost the load current to track the reference current. In a single-phase Z-source inverter, the shoot through states change the output voltage of the inverter to zero and due to this fact, a hysteresis current control based on the unipolar switching strategy can be a suitable current control technique for the Z-source inverter. In this method, a controller has to calculate the shoot through time and apply it in the switching states when the inverter output voltage is zero.

Fig. 6-a and Fig. 6-b show the control schematic of the unipolar hysteresis current control and switching signals for a Z-source inverter with shoot through states, respectively. Since the hysteresis current control has a variable switching frequency, thus the shoot through time \( T_s \) is estimated based on the previous switching cycle and Eq. 7. As shown in Fig. 6-b, the load current is compared with the reference current and the error signal is applied to two hysteresis controllers. The hysteresis controllers generate switching states for the power switches taking into account the shoot through time for boosting the output voltage. The shoot through switching states are applied to the inverter when the controller selects one of the zero voltage vectors. In this case, the magnitude of output voltage is zero and the shoot through does not affect the magnitude and waveform of the output voltage.

**IV. SIMULATION RESULTS**

In this paper a case study for the single-phase Z-source inverter with symmetrical and asymmetrical impedance network is performed based on unipolar hysteresis current control.

**A. Symmetrical impedance network**

In this section, a unipolar hysteresis band current control is applied to a single phase Z-source inverter with symmetrical impedance network \( (C_1=C_2=C \text{ and } L_1=L_2=L) \). Table II shows the system parameters.
### TABLE II

**SYSTEM PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input dc voltage (V_d)</td>
<td>100 volts</td>
</tr>
<tr>
<td>Load resistance (R_loa)</td>
<td>5 ohms</td>
</tr>
<tr>
<td>Load inductance (L_1, L_2)</td>
<td>3 mH</td>
</tr>
<tr>
<td>Z-network inductance (L_1, L_2)</td>
<td>1.6 mH</td>
</tr>
<tr>
<td>Z-network capacitance (C_1, C_2)</td>
<td>2 mF</td>
</tr>
<tr>
<td>Sinusoidal reference current</td>
<td>30 A</td>
</tr>
<tr>
<td>First current band</td>
<td>4 A</td>
</tr>
<tr>
<td>Second current band</td>
<td>5 A</td>
</tr>
</tbody>
</table>

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Fig. 6. Unipolar hysteresis current control for a single-phase Z-source inverter (a) control schematic (b) a typical switching sequence

Fig. 7. Switching pattern and load current tracking based on unipolar pulse width modulation

Fig. 8. Load current and voltage waveforms

Fig. 9. Load current, output voltage, capacitor voltage in Z-impedance, inductor current in Z-impedance

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Fig. 7 shows the load current and the output voltage of the inverter with the unipolar hysteresis current control. It shows that the Z-source inverter can generate a sinusoidal current with 30 A amplitude while the traditional inverter with 100 V (DC-link voltage) can generate a load current with 20 A amplitude in maximum case. The output voltage has the unipolar modulation waveform where for one half cycle the output voltage is changed between \(+V_{out}\) and zero voltage and another half cycle the output voltage is changed between \(-V_{out}\) and zero voltage. As shown in Fig. 7, when the load current crosses the second upper band at 0.07 S, the voltage level is changed from \(+V_{out}\) & Zero) to \(-V_{out}\) & Zero). Based on shoot through switching states the input voltage is boosted in such a way to generate the desired load current.

Fig. 8 shows the output voltage and load current for one cycle. In fact the objective of this control algorithm is not to control the DC voltage to a certain value; while the main objective is to generate the sine wave with higher magnitude and that is why there is ripple in the DC voltage which does not affect the output current.

Fig. 9 shows the load current and voltage waveforms, Z-network capacitor voltage and inductor current waveforms, respectively.
To evaluate the capabilities of hysteresis band current control for a single phase Z-source inverter to boost the input voltage and generate a sine wave load current, various conditions such as variation in the input DC voltage and the reference current magnitude are considered and simulated for this topology. As shown in Fig.10, an input DC voltage \( V_{dc} = 100 + 20 \sin \omega t \) is applied to the Z-impedance inverter. A shoot through controller calculates the shoot through intervals in such a way to generate a 30A sinusoidal load current and apply them to the switching states. Fig.10 shows the input dc voltage, the load current and voltage waveforms, the Z-network capacitor voltage, respectively.

![Fig.10. Input dc voltage, load current and voltage, Z-network capacitor voltage](image)

In order to analyse the effects of reference current changes on the capability of proposed control method, a sine wave with different magnitudes is applied where for the first two cycles, it has 30A, for the next two cycles its magnitude is 20A and finally with 30A in magnitude. Fig.11 shows the load current and voltage waveforms with respect to the reference current variations. Based on shoot through switching states which are calculated by the shoot through controller, the input dc voltage is boosted in such a way to generate the desired load current.

**B. Asymmetrical impedance network**

Because of 20% tolerance in capacitors \((C_1=1.2C, C_2=0.8C)\) and inductors \((L_1=1.2L, L_2=0.8L)\) the impedance network becomes asymmetric. In this section, effects of reference current changes on the capability of proposed control method with the asymmetrical Z-network configuration are investigated in such a way that a reference current is applied with waveform shown in Fig.11. In each case, load current and voltage waveforms are shown to verify the performance of the proposed control method. Simulation results show that a sinusoidal load current with desired amplitude can be obtained in asymmetrical Z-network.

In order to analyse a Z-impedance with different capacitor and inductor values, two different impedance networks have been considered for asymmetrical analysis:

- \( C_1=2.4\text{mF}, C_2=1.6\text{mF}, L_1=L_2=1.6 \text{ \mu H} \). Fig.12 shows load current and voltage waveforms with symmetrical inductors and asymmetrical capacitors.
- \( L_1=1.92 \text{ \mu H}, L_2=1.28 \text{ \mu H}, C_1=C_2=1 \text{ mF} \). Fig.13 shows load current and voltage waveforms with symmetrical capacitors and asymmetrical inductors.

![Fig.11. Load current and voltage with reference current variations](image)

![Fig.12. Load voltage and current waveforms in asymmetrical impedance network with symmetrical inductors and asymmetrical capacitors](image)
V. CONCLUSIONS

In this paper a unipolar hysteresis current control for a single phase Z-source inverter with shoot through states is analysed with symmetrical and asymmetrical impedance networks. Also effects of the input DC voltage and reference current fluctuations are analysed. Due to the shoot through switching states in the Z-impedance inverter, the unipolar pulse width modulation is a suitable modulation technique for a single-phase inverter. Simulation results show that the sinusoidal load current can be achieved by the Z-source inverter with higher magnitude compare to the traditional inverter. Switching states have been controlled in such a way to estimate the duty ratio for the shoot through switching states in order to boost the output voltage. Simulation results confirm the capabilities of the hysteresis current control for the Z-source inverter in DC-AC power conversion.

VI. REFERENCES