Performance Analysis of Single Stage Boost Inverter Using Quasi-Z Source Technique

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ABSTRACT: Quasi-Z-source inverter (QZSI) is a single stage power converter derived from the Z-source inverter topology, employing an impedance network which couples the source and the inverter to achieve voltage boost function. A new carrier based pulse width modulation (PWM) strategy for the QZSI which gives a significantly high voltage gain compared to the traditional PWM techniques is implemented. This technique employs triangular carrier wave and two dc signals along with two sine waves, with which the simple boost control for the shoot-through states is integrated to obtain an output voltage boost. Z source inverter is a new inverter that can be implemented in all types of power conversion. The circuit topology is based on modified voltage fed quasi z source inverter which suits to the light load or the heavy load and is fit for the resistive capacitive or inductive load. The evolution of renewable energy is being increased because of increasing price of fossil fuels and the growing problem of global warming. With great research, alternative renewable energy sources such as wind, water, bio-mass, geothermal and solar energy have been explored for electric power generation. Among the renewable energy sources, the solar energy is being widely utilized because of the free fuel, abundance, little maintenance and sustainability of solar radiant energy. Electrical energy is directly generated from the solar energy through the photovoltaic (PV) cells. In PV based power conditioning systems, the interface converter system acts as a key component. The impedance source inverter (ZSI) is employed as the interfacing converter conventionally.

KEYWORDS: V, I and Z source inverters, PWMInverter, Shoot Through stateand simple boost control.

I.INTRODUCTION

Inverter or power inverter is a device that converts the DC sources to AC sources. Inverters are used in a wide range of applications, from small switched power supplies for a computer to large electric utility applications in transport bulk power. This makes them very suitable when there is a need to use AC power tools or appliances.[1] Inversion is the change of dc power to ac power at a desired output voltage or current and frequency. A static semiconductor inverter circuit does this electrical energy inversion transformation. Conventionally, inverters are classified into two broad categories as voltage source inverter (VSI) and current source inverter (CSI).

Voltage Source Inverter

A VSI is one in which the dc input voltage would have to keep constant and independent of the load current drawn. The inverter dictates the load voltage while the drawn current shape is specified by the load. These topologies are widely used because they behave as voltage sources naturally as required in many industrial applications, such as adjustable speed drives (ASD’s), which are the most famous application of inverters. [4],[5] Similarly, these structures can be used as CSIs, where the independently controlled ac output is a current waveform. These structures are widely used in medium-voltage applications, where good-quality voltage waveforms are required. Static power converters, mainly inverters, are constructed from power switches and the ac output waveforms are therefore constructed of discrete values.

Limitations of VSI

The ac output voltage is limited below and cannot cross the dc-rail voltage. Therefore, the VSI is a buck inverter for dc-to-ac power conversion and the VSI is a boost rectifier for ac-to- dc power conversion. For applications where over drive is required and the available dc voltage is sufficient then an additional dc-dc boost converter is required to get the desired output. These additional converter stages raise the system cost and lower down the efficiency. The upper and lower devices of each phase leg cannot be gated on simultaneously otherwise, a shoot-through would occur which would destroy the devices. The shoot-through problem by electromagnetic interference (EMI) noises miss-gating on is
one of the main problems in terms of reliability of the converter. An output LC filter is required to provide a sinusoidal voltage compared with the CSI, which causes additional power loss.

Current Source Inverter
A CSI is one in which the source and therefore the load current is predetermined and the load impedance decides the output voltage. The supply current cannot change rapidly. This current is controlled by series inductance which control sudden changes in current. The magnitude of load current is controlled by varying the input dc voltage to the large inductance, hence inverter response to changing load is slow. Being a current source, the inverter may survive a short circuit thereby offering fault ride-through properties.

Limitations of CSI.
The output ac voltage has to be more than the original dc voltage which feeds the dc inductor. Therefore, the CSI is a boost inverter for dc-to-ac power conversion and the CSI is a buck inverter (or buck converter) for ac-to-dc power conversion. For applications where a wide voltage range is required, an additional dc to dc buck (or boost) converter is needed. The additional power conversion stage raises system cost and lowers the efficiency. At least one of the upper devices and one of the lower devices have to be gated on or turned on and maintained on at any time. Otherwise, an open circuit of the dc inductor would occur which would destroy the devices. The open-circuit problem by EMI noise miss-gating-off is a main concern in terms of reliability of the converter.[4],[5]

Impedance Source Inverter (QZSI)

With the introduction and wide acceptance of Z Source Inverter(ZSI) as an alternative for traditional voltage source and current source inverters (VSI/CSI), the modified switching schemes from the traditional schemes has reached the point where the further improvements in firing the switches and inserting the shoot-through states bring crucial benefits. In addition to the active switching states of the VSI, a ZSI has shoot-through zero states, when the positive and negative switches of a same phase leg are simultaneously switched on. This shoot-through state is harmful in VSI/CSI and can result short circuiting and damaging of entire application. Due to the capability of buck-boost and wide range of operating points, ZSI are suitable for the applications with unstable power supply such as fuel cell, wind power, photovoltaic etc.

The quasi z-source inverter (QZSI) is a single stage power converter derived from the Z-source inverter topology, employing a unique impedance network. The conventional VSI and CSI suffer from the limitation that triggering two switches in the same leg or phase leads to a short circuit and equipment destruction. And the maximum obtainable output voltage cannot exceed the dc input in the case of VSI, since they are buck converters and can produce a voltage lower than the dc input voltage. In the case of CSI they are boost converters. Both Z-source inverters and quasi-Z-source inverters overcome these drawbacks by utilizing several shoot-through zero states. A zero state is produced when the upper or lower switches are fired simultaneously to boost the output voltage. Sustaining the permissible active switching states of a VSI, the zero states can be partially or completely replaced by the shoot through states depending upon the voltage boostrequirement. Quasi-Z-source inverters (QZSI) acquire all the advantages of traditional Z Source inverter. The impedance network couples the source and the inverter toachievevoltage boost and inversion in a single stage. By using this new topology, the inverter draws a constant current from the source and is capable of handling a wide input voltage range.[7]

Outstanding features of QZSI
- Immune to short circuit fault
- Immune to open circuit fault
- Improved efficiency
- Better anti-interference ability
- Applicable to wide range of load
II. MAIN CIRCUIT TOPOLOGY AND ANALYSIS.

Fig. 2.1: Main Circuit Structure

II. MAIN CIRCUIT TOPOLOGY AND ANALYSIS.

Fig. 2.1 shows the circuit structure of the topology which based on quasi-Z-source network. It composes three parts: Input dc (battery, solar cell, and rectified dc), quasi Z source network and single phase Inverter Bridge. The structure of the Z-network is modified, compared to voltage fed Z-source inverter, that is, the position of the inductors, capacitors and the diode is different from that of voltage-fed Z-source inverter. This modification makes the average voltage of one of the quasi-Z-network capacitors decrease, and then, the cost, volume and weight of the whole system will also be decreased. Here the fully-controllable device VT5 is used in order to deal with the discontinuous operation condition when the load is light, it is an IGBT module which composed of an IGBT and an anti-parallel diode to replace discrete components. The diode here is necessary in the quasi-Z-source inverter. This modification mainly aims to solve the light load abnormal operation problem and when the load is normal, VT5 will not be turned on at all because its anti-parallel diode VD5 will keep on state during the non-shoot-through state.

The QZSI circuit differs from that of a conventional ZSI in the LC impedance network interface between the source and inverter. The unique LC and diode network connected to the inverter bridge modify the operation of the circuit, allowing the shoot-through state which is forbidden in traditional VSI. This network will effectively protect the circuit from damage when the shoot through occurs and by using the shoot-through state, the (quasi-) Z-source network boosts the dc-link voltage. There are several differences between the conventional and the current topology. The QZSI does not need a separate boost IGBT. The voltage boost is realized by switching a shoot through of the inverter during zero state. Due to the higher boosting frequency the circuit devices L1, L2, C1, and C2 can be designed smaller accordingly, that is, the capacities are within a range of few Farads. In addition, the capacitors do not need to be electrolytic but can be film capacitors, whose lifetime is not dependent on ambient temperature. For regeneration the QZSI only needs one additional power electronic device, named VT5 when supply to load like electric vehicles engine. With the use of QZSI to supply the electric vehicle’s engine the electrolytic capacitor’s lifetime restrictions and the effort to control more additional power electronic devices do not apply, contrary to the conventional topology.

III. OPERATING PRINCIPLE

There are 3 states of operation for the QZSI network. The Quasi-Z-source network is combination of split inductors L1 and L2, and capacitors C1 and C2 for coupling of the inverter network to dc source. The inverter network can be either single-phase or three-phase but the focus here is for single-phase QZSI. The end of the block is an ac load, which can be connected to the load or to another converter. There are three switching states possible when operating the QZSI. Two of them are well known from the conventional topology: the active state (AS) and the zero state (ZS). In addition there is a third mode, the shootthrough state (ST). This third state is needed to boost the voltage and its duration per switching cycle indicates the voltage rate.
Active State

In the non-shoot through mode, in figure 2.2 the switching pattern for the QZSI is similar to that of a VSI. The inverter bridge, viewed from the DC side is equivalent to a current source. The input dc voltage is available as DC link voltage input to the inverter, which makes the QZSI behave similar to a VSI. The voltage across the load in this state is greater than zero.

Traditional Zero State

In the states shown in figure 2.3, the upper and lower two switches are turned on simultaneously and the power does not flow to the load. In this case the output is an open circuit and it acts as zero value current source. Hence this traditional zero state can be integrated to the active state to form a Non shoot through state.

Shoot Through Zero State
The third state shown in figure 2.4, the shoot through state, is usually switched at the beginning and/or end of zero state when the voltage across the load is zero. In the shoot through mode, switches of the same phase VT1 and VT4 or VT2 and VT3 in the inverter bridge are switched on simultaneously for a very short duration. The source however does not get short circuited when attempted to do so because of the presence of LC network, while boosting the output voltage. The DC link voltage during the shoot through states, is boosted by a boost factor, whose value depends on the shoot through duty ratio for a given modulation index.

### Table 2.1 Analysis of Voltages and Currents

<table>
<thead>
<tr>
<th>AS</th>
<th>ZS</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load/Output</td>
<td>v &gt; 0, i ↑</td>
<td>v = 0, i ↓</td>
</tr>
<tr>
<td>L1, L2</td>
<td>v &lt; 0, i ↑</td>
<td>v &lt; 0, i ↓</td>
</tr>
<tr>
<td>C1, C2</td>
<td>v ↑, i &gt; 0</td>
<td>v ↑, i &gt; 0</td>
</tr>
<tr>
<td>Diode</td>
<td>v = 0, i &gt; 0</td>
<td>v = 0, i &gt; 0</td>
</tr>
</tbody>
</table>

The table shows the theoretical analysis of voltages and currents and the behaviour of all quantities across inductances, capacitances and diode in all three possible states (Active state, traditional zero state, Shoot through state). The diode within the intermediate state can change the status during active state and zero state from conductive to blocking. This occurs if the diode current becomes less than or equal to zero.

### IV. Circuit Analysis

Assuming that during one switching cycle Time T, the interval of the shoot-through state is T0, the interval of non-shoot-through states is T1, thus $T = T0 + T1$ and the shoot-through duty ratio $D$ is $T0/T1 = D$.

During the interval of the non-shoot through state T1

From Reference Figure 2.3

$U_i = U_{L1} + U_{C2} \ldots \ldots \ldots (2.1)$

$U_{L2} = U_{C1} = U_{C2} - U_{inv} \ldots \ldots \ldots (2.2)$

During the interval of the shoot through state T0

From Reference figure 2.4

$U_{L2} = U_{i} - U_{C1} \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2.3)$

$U_{L2} = U_{C2}; U_{inv} = 0 \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2.4)$

The average voltage of the quasi-z-network inductors should be zero in a switching period

From equations 2.1 to 2.4

\[
UL2 = \left( \frac{U1 + U2}{2} \right) + \frac{T0 + U2}{T} \]

\[
U_{L2} = \frac{T1 \times (U_{C1} - U_{inv}) + T0 \times U_{inv}}{T} \ldots \ldots \ldots (2.5)
\]

Or

\[
UL2 = \frac{T1 \times (U_{C1} - U_{inv}) + T0 \times U_{inv}}{T} \ldots \ldots \ldots (2.6)
\]

\[
u_{C1} = \frac{T1}{T} \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2.7)
\]

\[
u_{C2} = \frac{T0}{T} \ldots \ldots \ldots \ldots \ldots \ldots \ldots (2.8)
\]

\[
u_{inv} = m \times U_{inv} = B \times m \times U_{i} \ldots \ldots \ldots (2.9)
\]

B = Boost factor = Duty ratio = Modulation index. The minus sign of UC1 indicates the actual polarity of the voltage of capacitor C1 is opposite of the polarity shown in the circuit. As the voltage rating of the capacitor is decreased compared to that of voltage fed source inverter, the whole system has less weight and volume. Hence QZSI inherits all advantages of the ZSI. It can buck or boost a voltage with a given boost factor. It is able to handle a shoot through state.
and therefore it is more reliable than the traditional VSI. It is unnecessary to add a dead band into control schemes, which reduces the output distortion.

INVERTER SECTION

As the shoot-through zero state is inserted in the traditional zero state, this network will provide boost function to the novel Z-source or quasi-Z-source inverter, and will not lead to the deterioration of the PWM control of the inverter. The insertions of shoot-through zero state will increase the switching times of the power switches of the inverter bridge, and it will increase the power loss of the switches. The switching orders can be reasonably arranged to decrease the switching times. The operate state of a bridge leg is defined by three values 1, 0, and x, where 1 denotes the upper switch is on and the lower switch is off, 0 denotes the upper switch is off and the lower switch is on, and x denotes both the upper switch and the lower switch are on.

Table 3.1: Operating States and Switch Transition

<table>
<thead>
<tr>
<th>Operation States</th>
<th>10</th>
<th>X0</th>
<th>00</th>
<th>0X</th>
</tr>
</thead>
<tbody>
<tr>
<td>On State Switch</td>
<td>VT1,VT3</td>
<td>VT1,VT3,VT4</td>
<td>VT3,VT4</td>
<td>VT2,VT3,VT4</td>
</tr>
<tr>
<td>Switch Transition</td>
<td>VT2 off</td>
<td>VT4 on</td>
<td>VT1 off</td>
<td>VT2 on</td>
</tr>
<tr>
<td>Operation States</td>
<td>01</td>
<td>x1</td>
<td>11</td>
<td>1x</td>
</tr>
<tr>
<td>On State Switch</td>
<td>VT2,VT4</td>
<td>VT1,VT2,VT4</td>
<td>VT1,VT2</td>
<td>VT1,VT2,VT3</td>
</tr>
<tr>
<td>Switch Transition</td>
<td>VT3 off</td>
<td>VT1 on</td>
<td>VT4 off</td>
<td>VT3 on</td>
</tr>
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<td>Operation States</td>
<td>10</td>
<td></td>
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<tr>
<td>Switch Transition</td>
<td>VT2 off</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Therefore, the single-phase voltage fed quasi-Z-source inverter will have nine operating states, they are 10, 01, 00, 11, 0x, x0, x1, 1x, xx. If only single inverter leg be shoot through is allowed, the xx state will be excluded. Then the switch order will be as 10, x0, 00, 0x, 01, x1, 11, 1x, 10 as given in table. By choosing this order each state transition only need to turn on or turn off one switch, for example, 10 to x0 only need to turn on VT4 and then x0 to 00 only need to turn off VT1, etc. This will significantly decrease the switching times, so it increases the switching frequency and will not damage the power switches. The operation states and switch transition of the voltage-fed single phase quasi-Z-source inverter are shown in table 3.1.

V. CONTROL STRATEGY

The QZSI configuration has six active vectors when the DC voltage is impressed across the load and two zero vectors when the load terminals are shorted through either lower or upper three switches. These total eight switching states and their combinations have been spawned many PWM control schemes. Sinusoidal PWM is the most commonly used PWM technique in the VSI. On the other hand, QZSI has additional zero vector or shoot through switching states that are forbidden in traditional VSI. For an output voltage boost to be obtained, a shoot through state should always be followed by active state. Three phase inverter must be controlled so that at no time both the switches in the same leg are turned on or else the DC supply would be shorted. This requirement may be met by the complimentary operations of the switches within a leg. There are three PWM strategies:

1. Simple boost control
2. Maximum Boost control
3. Maximum constant boost control.
Simple boost control technique is used for this circuit

Simple boost control
The main idea of simple boost control method is using two DC voltage signals and two AC voltage signals as modulation waves, compared with the high frequency carrier triangle wave, the value of the DC voltage could higher than or even equal to the peak value of the AC voltages, then the control signals of the inverter bridge switches are obtained. To simplify the control circuit and decrease switch voltage stress, the DC voltage value often chosen should be equal to the peak value of the AC modulation wave; in this case, it is chosen that \( m + D = 1 \), and the shoot-through zero state duty cycle \( D \) is a constant value. Two straight lines are employed to realize the shoot through duty ratio. The upper one will be the peak value of the sinusoidal wave. When the triangular carrier wave is greater than the upper envelope \( V_p \) or lower than the lower envelope \( V_n \) the circuit turns to the shoot through state, otherwise the circuit operates just as traditional carrier based PWM [9], [10]

VI. SIMULATION & RESULTS

Simulation Diagram

Simulation Results & Waveforms
To verify the analysis Simulation of QZSI is carried out for an input voltage of 24V, Duty cycle of 0.3. For a switching frequency of 20kHz the components are chosen as \( C_1 = C_2 = 1000\mu\text{F}, L_1 = L_2 = 2\text{mH} \), connected to a RL load. The simulation results are shown in the simulation waveforms. In the Boost mode, for an input DC voltage of 24V, an output AC voltage of 40V (avg) and output current of 10Amps is obtained. In the Buck mode for an input voltage of 24V, an output AC voltage of 7V and current of 0.3Amps is obtained.
Output Current Waveform & Output Voltage Waveform (Boost mode)

Output Current Waveform & Output Voltage Waveform (Buck mode)

Simulation Results

<table>
<thead>
<tr>
<th>Modulation index</th>
<th>Output Voltage</th>
<th>Output Current</th>
<th>Capacitor Voltage C1</th>
<th>Capacitor Voltage C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>M=0.7 (Boost mode)</td>
<td>40V</td>
<td>1.75A</td>
<td>20V</td>
<td>50V</td>
</tr>
<tr>
<td>M=0.3 (Buck mode)</td>
<td>7V</td>
<td>0.3A</td>
<td>2V</td>
<td>22V</td>
</tr>
</tbody>
</table>

Applications of QZSI
- Adjustable speed drives, motor drives
- Grid connected photovoltaic systems
- Uninterruptable power supply
- Super capacitor energy storage
- Electric vehicles

VII. CONCLUSION

In this paper, Single stage QZSI concept has been introduced. The proposed converter employs a QZSI to couple the converter main circuit to the power source. With this configuration, the proposed inverter has the following features that cannot be obtained with conventional V-source and I-source structures.

1) The proposed converter can be short- and open circuited without damaging switching devices. Therefore, it is very resistant to EMI and its robustness and reliability are significantly improved.
2) It has both buck and boost functions. QZSI can be applied to ASD. Their
application to ASD will show better results than VSI/CSI fed ASD. Output voltage can be greater or smaller than input voltage. Thus, it is a very desirable circuit topology when the input voltage range of the converter is wide. The operating principle of the proposed inverter was analysed in detail and simulation is carried out.

REFERENCES