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Selection of suitable Topology and Switching Technique of ZSI for wind power application

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Abstract

A comparative study of three topologies of recently developed voltage-fed z-source inverter (ZSI) such as simple ZSI, quasi-ZSI and trans-QZSI is presented in this paper. Different control techniques, proposed earlier for simple ZSI such as simple boost control, maximum boost control and constant boost control, have been applied here for all type of ZSI topologies. The detailed comparative evaluation of all topologies under different control techniques is done in wind power applications. For the common boost factor and modulation index, the output voltage of all ZSIs with same dc power supply and load are evaluated. The operating principles are analysed and the boost factor, voltage gain, duty ratio and voltage stress across the switches are derived. The relationships among them are compared even under variable circuit parameters and switch frequency which suggests trans-QZSI with maximum constant boost control switching technique as the most suitable combination for the wind power application.

Keywords

Z-source inverter, Buck-boost, Pulse width modulation (PWM), Topology, Shoot-through

1. Introduction

Wind is an intermittent source of energy and the output voltage and frequency from wind generator vary for variable wind velocities. This variable nature of output is the major drawback of wind power system. Traditionally, this variable AC power from this generator is rectified first into DC and then is regulated for constant voltage by using dc to dc converter. The constant DC output then is fed to the load at the required level of voltage and frequency using PWM inverter. The major requirement in the wind energy system is to realize and maintain consistently a constant voltage at the load terminal. Conventional voltage-source inverters (VSIs) have some limitations like the obtainable ac output voltage cannot exceed the dc source voltage. So a dc–dc boost converter is needed additionally in the applications. Again, the dead time is required for switching signals to prevent the short circuit of the upper and lower switching devices of each phase leg of VSI. However, it induces waveform distortion. It is proposed [1] to employ impedance (Z) source inverter in place of conventional inverter. The boost capability of impedance source inverter is expected to control both the input voltage and load variations.

Proposed z-source inverter (ZSI) [2] can overcome the above problem and limitation. It is becoming attractive because it continues to employ a conventional VSI as the power converter with an additional z-network for modified dc link stage. It allows the VSI to operate in a shoot-through state where the two switching devices in the same inverter leg are simultaneously switched-on to effect a short circuit to the dc link. Because of some advantages of ZSI, it has been proposed for various applications like ac motor drives [3], fuel cell [4], uninterruptible power supplies [5], photovoltaic systems [6,7], electric vehicle [8] etc.

However, the main drawback of the voltage-fed ZSI is that the input current is discontinuous in the boost mode and the z-network capacitors sustain a high voltage.

Again, there are different control strategies proposed for the ZSI namely simple boost control [3], maximum boost control method [9], constant boost control method [10] etc. The simple boost control (SBC) method is considered very straightforward but it has some disadvantage like the resulting voltage stress across the switches is relatively high. The Maximum boost control (MBC) method can also be used to extend the modulation index range turning all zero states into shoot-through states to minimize the voltage stress. At the same time, this method introduces a low frequency current ripple that is associated with the output frequency in the inductor current and the capacitor voltage. This causes higher requirement of the passive components when the output frequency becomes very low. On the other side, constant boost control (CBC) method can be adopted to eliminate the low frequency ripple present and thus to reduce the size of L-C in the z-network. In order to reduce the volume and cost, it is always desirable to keep the shoot-through duty ratio constant. At the same time, a greater voltage boost for any given modulation index is required to reduce the voltage stress across the switches. The maximum constant boost control achieves the maximum voltage gain while always keeping the shoot-through duty ratio constant.

Also, some new converter topologies based on the ZSI concept have been proposed to improve the performance of the original converter. Quasi ZSI (qZSI) topology is proposed in [11] to further improve on the traditional ZSIs. The qZSIs also have several additional merits like reduced passive component ratings, continuous input current configuration, a common dc rail between the source and inverter.

Again, the voltage stress on capacitor is reduced which ultimately lower the voltage stress on the inverter bridge and the input dc current (and inductor current) is continuous when compared to the traditional ZSI. For the voltage fed Trans_ZSI proposed in [12], one of the capacitors is removed and coupled inductor is introduced in place of discrete two inductors. When the turns ratio of the two windings is over 1, the voltage-fed trans-Z-source inverter can obtain a higher boost gain with the same shoot-through duty ratio and modulation index, compared with the original Z-source inverter. This topology is proposed in [13] and named as Trans-qZSI. The proposed new topologies mentioned above are evaluated in general and not for any particular application. Their performance is not also studied under different switching control techniques. Though all the ZSIs are more or less suitable for wind power system, a comparative evaluation is necessary for their performance under wind power application.

2. Theoretical Analysis

A. Traditional voltage-fed ZSI

The peak value of the phase voltage of the inverter output derived from the figure 1 is $V_{ph} = \frac{MBV_{in}}{2}$, where M is the modulation index and B is the boost factor resulting from the shoot through zero state and their product is the overall gain G.

The voltage across each capacitor can be expressed as $V_C = \frac{1-D}{1-2D} * V_{in}$.

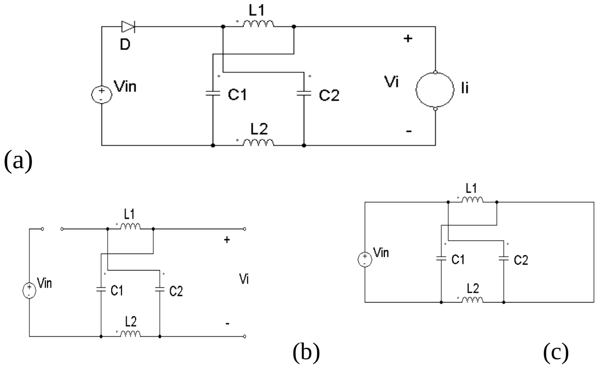


Figure 1: Traditional voltage-fed ZSI (a) equivalent circuit (b) non shoot-through state (c) shoot-through state

For simple boost control method used in the ZSI topology, then from (1) we have D= 1-M,

Boost factor $B = \frac{D}{1-2D} = \frac{1}{2M-1}$.

Voltage gain $G = MB = \frac{M}{2M-1}$.

Switching stress $V_S = BV_{in} = \frac{V_{in}}{2M-1}$

If maximum boost control method is used in the ZSI topology, then from (1) we have $D = \frac{2\pi - 3\sqrt{3}M}{2\pi}$

Boost factor $B = \frac{2\pi}{6\sqrt{3}M - 2\pi}$

Switching stress $V_S = BV_{in}$

In case of maximum constant boost control method in the ZSI topology, eqn (1) gives $D = \frac{2-\sqrt{3}M}{2}$

Boost factor $B = \frac{1}{\sqrt{3}M - 1}$

Switching stress $V_S = BV_{in} = (\sqrt{3}G - 1)V_{in}$

B. Voltage-fed quasi-ZSI

In non-shoot through state of Figure 2(b),

$V_{L2} = -V_{C2}$, $V_{L1} = V_{in} - V_{C1}$

$$V_i = V_{C1} - V_{L2} = V_{C1} + V_{C2} \text{ ,} V_{Diode} = 0$$

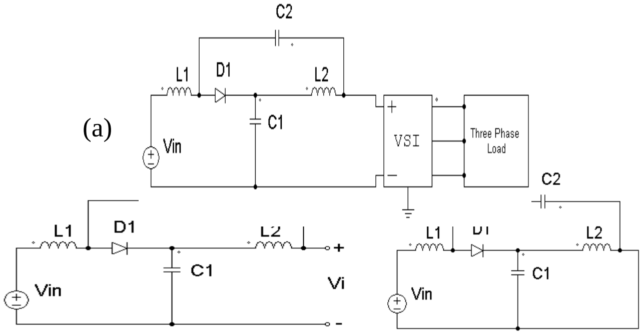
In shoot through state from figure 2(c),we may write

$V_{L2} = V_{C1}$, $V_{L1} = V_{C2} + V_{in}, V_i = V_{C1} + V_{C2} = 0$

Considering the average voltage across an inductor over one switching period is zero, we have

$$V_{L1} = \overline{v_{L1}} = \frac{(V_{in}+V_{C2})T_0 + (V_{in}-V_{C1})T_1}{T} = 0 \text{...............}(2)$$

$$V_{L2} = \overline{v_{L2}} = \frac{(-V_{C2})T_1 + V_{C1}T_0}{T} = 0 \text{..................................}(3)$$



(b) (c)

Figure 2: Voltage-fed quasi ZSI (a) equivalent circuit (b) non shoot-through state (c) shoot-through state

From (2) and (3) we get

$$V_{C1} = \frac{T_1}{T_1 - T_0} V_{in} \text{ , } V_{C2} = \frac{T_0}{T_1 - T_0} V_{in}$$

So $V_i = V_{C1} + V_{C2} = \frac{1}{1-2D} V_{in} = BV_{in}$

Where B = $\frac{1}{1-2D}$ = Boost factor (4)

For simple boost control method is used in the qZSI topology then from (4) we have $B = \frac{1}{2M-1}$.

Since the boost factor B is same as that of the traditional ZSI so all the parameters like $M_{\max}$, switching stress and peak of the output phase voltage are same with the traditional ZSI.

Again, if maximum boost control method is used in the qZSI topology then from (4),

We have $D = \frac{2\pi - 3\sqrt{3}M}{2\pi}$,

So, Boost factor $B = \frac{1}{1-2D} = \frac{2\pi}{6\sqrt{3}M - 2\pi}$

Again for maximum constant boost control method in the qZSI topology then from (4)

We have $D = \frac{2-\sqrt{3}M}{2}$

So, $B = \frac{1}{\sqrt{3}M - 1}$

Now for qzsi, from (4) we may write

$\frac{V_{C1}}{V_{in}} = \frac{T_1}{T_1 - T_0} = \frac{1-D}{1-2D}$ and

$\frac{V_{C2}}{V_{in}} = \frac{T_0}{T_1 - T_0} = \frac{D}{1-2D}$

Now voltage across the inductor L1 in the shoot through and non-shoot through states respectively are

$V_{C2} + V_{in} = \frac{D}{1-2D} V_{in} + V_{in}$ and

$V_{in} - V_{C1} = V_{in} - \frac{1-D}{1-2D} V_{in}$

So, overall voltage across L1 can be represented by the switching function S_f which is 1 when the voltage-fed inverter is in the shoot-through zero states and 0 when it is in the non-shoot through states.

$$V_{L1} = (\frac{D}{1-2D} V_{in} + V_{in}) S_f + (V_{in} - \frac{1-D}{1-2D} V_{in}) \overline{S_f}$$

And therefore, $\frac{V_{L1}}{V_{in}} = \frac{S_f - D}{1-2D}$

Similarly, voltage across the inductor L2 can be represented as

$V_{L2} = (\frac{1-D}{1-2D} V_{in}) S_f + \overline{S_f} \frac{(-D)}{1-2D} V_{in}$ and so

$\frac{V_{L2}}{V_{dc}} = \frac{S_f - D}{1-2D}$

Again, voltage across the inverter bridge in the shoot through and non-shoot through states respectively are

$V_i = 0$ And

$$V_i = V_{C1} - V_{L2} = V_{C1} + V_{C2} = \frac{1-D}{1-2D} V_{in} + \frac{D}{1-2D} V_{in}$$

So, the inverter bridge voltage can be represented by the switching function S_f as

$V_i = 0 \times S_f + (\frac{1-D}{1-2D} V_{in} + \frac{D}{1-2D} V_{in}) \overline{S_f}$ And so $\frac{V_i}{V_{in}} = \frac{\overline{S_f}}{1-2D} \geq 0 \cdot$

The current drawn from the DC source is same as the current through the inductor L1.

C. Voltage-fed Trans ZSI

In trans-ZSI shoot through state from figure 3(b) we can write,

$$V_{L1}=V_{in}+V_d-V_{C1}=\frac{1}{n}V_{L2}=\frac{1}{n}V_{C1}$$

In non-shoot through state from figure 3(c),

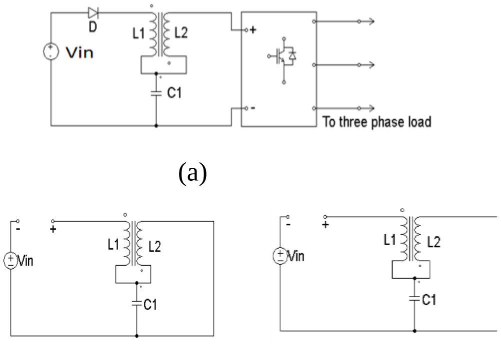
$$V_{L1}=V_{in}-V_{C1}$$

Now average voltage across an inductor over one switching period is zero, therefore we have

$$V_{L1}=\overline{v_{L1}}=\frac{(\frac{1}{n}V_{C1})T_0+(V_{in}-V_{C1})T_1}{T}=0$$

Or $\frac{V_{C1}}{V_{in}}=\frac{n(1-D)}{n-(1+n)D}$

In trans ZSI n=1 , therefore $\frac{V_{C1}}{V_{in}}=\frac{(1-D)}{1-2D}$



(a)

(b) (c)

Figure 3: Voltage-fed trans ZSI (a) equivalent circuit (b) shoot-through state (c) non shoot-through state

Now to find the voltage across the inverter bridge, in shoot through state voltage across the inverter bridge $V_{in}=0$.

In non shoot through $V_i=V_{c1}(1+n)-nV_{in}$

Therefore, the average DC link voltage across the inverter bridge becomes

$$\overline{v_i}=\frac{0*T_0+[V_{C1}(1+n)-nV_{in}]T_1}{T}=\frac{n(1-D)}{n-(1+n)D}V_{in}=V_{C1}$$

Now the peak DC link voltage across the inverter bridge is

$$\overline{V_i}=V_{C1}-V_{L1}=\frac{n(1-D)+D}{n-D(1+n)}V_{in}=BV_{in}$$ Where

B=Boost factor = $\frac{n(1-D)+D}{n-D(1+n)}$ (5)

Again, if simple boost control method is used in the Trans ZSI topology then from eqn (6) we have

B= $\frac{nM+1-M}{nM+M-1}$ as D=1–M

Gain G=M* $\frac{nM+1-M}{nM+M-1}$

Switching stress $V_S=BV_{in}=\frac{nM+1-M}{nM+M-1}V_{in}$

In case of maximum boost control method, used in the Trans ZSI topology then from (5)

$$B=\frac{2\pi n+(1-n)(2\pi-3\sqrt{3}M)}{2\pi n-(1+n)(2\pi-3\sqrt{3}M)}$$

As $D=\frac{2\pi-3\sqrt{3}M}{2\pi}$

Gain G = M * $\frac{2\pi n+(1-n)(2\pi-3\sqrt{3}M)}{2\pi n-(1+n)(2\pi-3\sqrt{3}M)}$

Switching stress

$$V_s=V_{in}=\frac{2\pi n+(1-n)(2\pi-3\sqrt{3}M)}{2\pi n-(1+n)(2\pi-3\sqrt{3}M)}V_{in}$$

If Maximum constant boost control method is used in the Trans ZSI topology, the (6) becomes

$$B=\frac{2n+(1-n)(2-\sqrt{3}M)}{2n-(1+n)(2\pi-\sqrt{3}M)}$$

As $D=\frac{2-\sqrt{3}M}{2}$

Gain $G=\frac{2n+(1-n)(2-\sqrt{3}M)}{2n-(1+n)(2\pi-\sqrt{3}M)}M$

Switching stress

$$V_S=BV_{in}=\frac{2n+(1-n)(2-\sqrt{3}M)}{2n-(1+n)(2\pi-\sqrt{3}M)}V_{in}$$

From the above derivations, the voltage across the inductor is easily derived using switching function S_f and considering n=1.

$$\frac{V_{L1}}{V_{in}} = \frac{1-D}{1-2D} \times S_f + (\frac{-D}{1-2D} V_{in})\overline{S_f} = \frac{1}{1-2D} S_f - \frac{D}{1-2D}$$

$$\frac{V_{L2}}{V_{in}} = \frac{1}{1-2D} \times S_f - \frac{D}{1-2D}$$

The parameters presented as a function of modulation index (M) are duty cycle (D), boost factor (B), and overall gain of the inverter (G). The maximum possible Modulation index $M_{\max}$ and voltage stress across switch are expressed in terms of gain G.

3. Results & Discussion

A comparative study is carried out under SIMULINK environment for all the three types of z-source converters with three different modes of control strategies. The study is done based on its capability of maintaining a constant three phase output voltage irrespective of parameters and shoot-through duty cycle but under a constant dc input. The modulation index and switching frequency are kept constant under this study. To keep output voltage constant, the duty cycles are varied and circuit parameters are adjusted accordingly. To maintain smooth sinusoidal at the output, the filter size is also adjusted. Specifications are selected for the simulation work is as below:
Source voltage, Vin=150 V,
Modulation index, M=0.9 and
Switching frequency, fs = 10 kHz,
Load resistance, R_L =5 ohms, Load inductance, L_L =2mH,

It shows that constant boost control is the best among all the controls. The size of L and C required are less in case of trans-qZSI but output contains more harmonics and therefore filter size increases. Some more measurements of voltage and currents are taken in the simulation and presented in Table 1. They are the input dc current I_{in}, voltage across capacitors $(V_{C1} = V_{C2})$, voltage across inductors $(V_{L1} = V_{L2})$, current through inductors $(I_{L1} = I_{L2})$, switching stress (V_S). Voltage as well as current through L is more in case of Trans QZSI, but no significance change in capacitor voltage.

Table 1: Results of different voltages and currents for all type of ZSI under different PWM control

Topology	**Control method**	I_{in} **(Avg)amp**	V_s ***(Avg)*** **volt**	V_{C1} **(Avg) volt**	V_{C2} **(Avg) volt**	V_{L1} **(rms) volt**	V_{L2} **(rms) volt**	I_{L1} **(rms) amp**	I_{L2} **(rms) amp**
ZSI	SBC	37	357	709	709	369	369	80	80
	MBC	37	282	560	560	326	326	54	54
	CBC	37	313	640	640	366	366	84	84
QZSI	SBC	39	437	723	873	853	783	179	146
	MBC	37	321	478	628	437	437	55	55
	CBC	37	334	516	667	399	415	85	110
TRANS_QZSI n1:n2 =1:2	SBC	39.5	354	533	-	570	715	123	123
	MBC	39.6	269	384	-	831	1007	81	81
	CBC	39	314	461	-	508	650	120	120

In Maximum boost control method having variable shoot-through duty cycle, high inductance is required since the inductor current has six times load frequency current ripple. Also, there are large oscillations in both the capacitor voltage and the inverter input voltage which increases the voltage stress in the power switching. In SBC, MBC and CBC methods the shoot-through current is equally distributed on the three phases of the inverter bridge which limit the current stress on the switch. Maximum boost control method introduces a low frequency current ripple associated with the output frequency in the inductor current and the capacitor voltage. This will cause a higher requirement of the passive components when the output frequency becomes very low. Hence the maximum boost control is suitable for applications that have a fixed or relatively high output frequency. Constant boost control method is very suitable for minimizing the *Z*-source network, especially in low-frequency.

4. Conclusions

In this paper, three major types of pulse width modulation control methods for three recently proposed three phase voltage fed Z-source inverters (ZSI) have been explored and compared. Comparison is done based on their capability of providing constant voltage at the output under variable input condition of wind generator. The boost factor, voltage gain, duty ratio, and voltage stress across the switches for each method have been analyzed in detail. The theoretical nature of capacitor voltages, inductor currents and input currents are derived with suitable mathematical expression and supported by simulation numerical results. Harmonic profile of their outputs are also studied and compared. Most suitable topology for wind power application is found to be as Trans quasi ZSI with maximum constant boost control PWM switching technique.

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