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A new low cost single phase ac-ac power line conditioner

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Abstract

The paper presents a comparative study of three topologies of recently developed voltage-fed z-source inverter (ZSI) such as simple ZSI, quasi-ZSI and trans-ZSI. 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 PWM techniques is done as power line conditioner. For the common boost factor and modulation index, the output voltage, line harmonics profile of all ZSIs powered by same source 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. Also the relationships among them are compared even under variable circuit parameters and switch frequency. The results would help to select suitable topology and PWM switching method for power line conditioner application.

Keywords

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

1. Introduction

Variation of output voltage and frequency for a number of reasons in any power system is a common characteristic today. This inconsistency in output is the major drawback of wind power system also. Traditionally, the variable AC power from this wind 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 employing a PWM inverter. The major requirement in this system is to realize and maintain consistently a constant voltage and frequency at the load terminal. Conventional voltage-source inverters (VSIs) have some limitations like the obtainable ac output voltage cannot exceed the dc source voltage. Also, 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 system. The boost capability of impedance source inverter is expected to take care both the input voltage and load variations. Z-soure inverter (ZSI) proposed [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. Due to 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.

Moreover, there are different control strategies proposed for the ZSI namely simple boost control [9], maximum boost control method [10], constant boost control method [11] etc. Simple boost control (SBC) method is very straightforward but it has some disadvantage like the resulting voltage stress across the switches is relatively high. 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. But, 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. So, the maximum boost control is suitable for applications that have a fixed or relatively high output frequency. 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.

Again, 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 [12] 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, and so on. Also, the voltage stress on capacitor is reduced that 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. In case of voltage fed Trans_ZSI proposed in [13], one of the capacitors is removed and coupled inductor is introduced in place of discrete two inductors. It has less voltage stress across the active switch for the same voltage gain. The circuit is useful to the dc-ac application demanding high voltage gain from low voltage dc source. 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. Simple voltage-fed ZSI

The peak value of the phase voltage of the inverter output derived from the fig. 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.

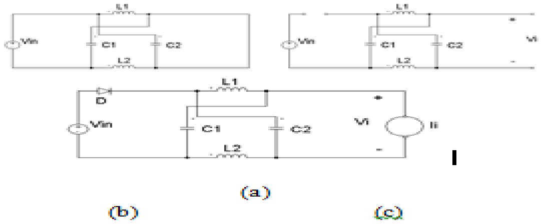


Fig. 1: Conventional voltage-fed ZSI (a) equivalent circuit (b) non shoot-through state (c) shoot-through state

$$B = \frac{T}{T_1 - T_0} = \frac{1}{1-2D} \text{..............................(1)}$$

where D=shoot through duty ratio. For the traditional voltage source PWM inverter we have the well known relationship as

$V_{ph} = M\,\frac{V_{in}}{2}$ The voltage across each capacitor of ZSI can be expressed as $V_c = \frac{1-D}{1-2D} V_{in}$

Now if simple boost control method is used in the ZSI, then from eqn (1) we have D= 1-M,

Boost factor =

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

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

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

Peak of the output phase voltage $V_{ph} = \frac{MBV_{in}}{2} = \frac{MV_{in}}{4M-2}$

If maximum boost control method is used in the ZSI topology, then from eqn (1) we have

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

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

Switching stress $V_S = BV_{in} = \frac{3\sqrt{3}G - \pi}{\pi} V_{in}$

Peak of the output phase voltage

$$V_{ph} = \frac{MBV_{in}}{2} = \frac{\pi M V_{in}}{6\sqrt{3}M - 2\pi}$$

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

Peak of the output phase voltage,

$$V_{ph} = \frac{MBV_{in}}{2} = \frac{MV_{in}}{2\sqrt{3}M - 2}$$

B. Voltage-fed quasi-ZSI

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

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

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

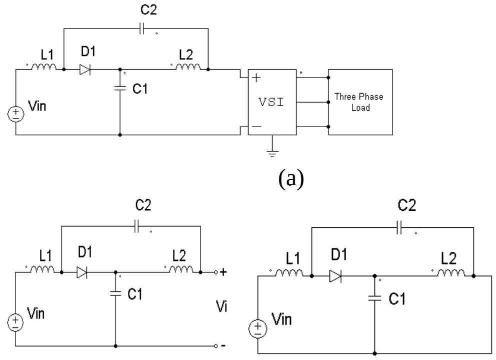
Also, in shoot through state from Fig. 2(c),we may write

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

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

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

$$\overline{v_{L1}}=\frac{(-V_{C2})T_1+(V_{C1})T_0}{T}=0.....(3)$$



(a)

(b) (c)

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

From (2) and (3) we get

$$V_{C1}=\frac{T_1}{T_1-T_0}V_{in}, V_{c2}=\frac{T_0}{T_1-T_0}V_{in}........(4)$$

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

where $B=\frac{1}{1-2D}$............(5)

For simple boost control method is used in the qZSI topology then from eqn (5) we have $B=\frac{1}{2M-1}$.

As 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.

Now if maximum boost control method is used in the qZSI topology then from eqn (5) we have

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

So, boost factor

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

Peak of the output phase voltage

$$V_{ph}=\frac{MBV_{in}}{2}=\frac{\pi MV_{in}}{6\sqrt{3}M-2\pi}$$

Again for maximum constant boost control method in the qZSI topology, we have from eqn (5)

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

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

Peak of the output phase voltage

$$V_{ph}=\frac{MBV_{in}}{2}=\frac{MV_{in}}{2\sqrt{3}M-2}$$

Now for qZSI, from eqn (4) we may write

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

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

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 so $\frac{V_{L1}}{V_{in}}=\frac{S_f-D}{1-2D}$

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

$$V_i = 0\times S_f + \left(\frac{1-D}{1-2D}V_{in} + \frac{D}{1-2D}V_{in}\right)\overline{S_f}$$

and so, $\frac{V_i}{V_{in}} = \frac{\overline{S_f}}{1-2D} \geq 0$

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 Fig. 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 Fig. 3(c),

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

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

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

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

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

Again, to find the voltage across the inverter bridge, in shoot through state voltage across the inverter bridge $V_i = 0$.

In non shoot through $V_i = V_{C1}(1+n) - nV_{in}$

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

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

Now the peak DC link voltage across the inverter bridge is

$$V_{i_{peak}} = V_{C1} - V_{L1} = \frac{n(1-D)+D}{n-D(1+n)}V_{in} = BV_{in}$$

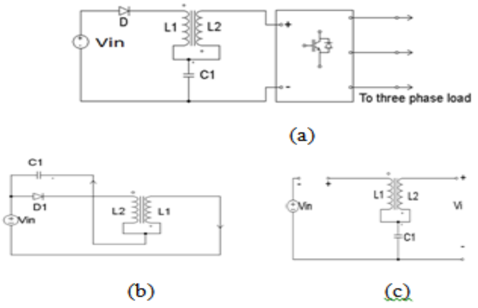


Fig. 3: Voltage-fed trans ZSI (a) equivalent circuit (b) shoot-through state (c) non shoot-through state

Where $B = \frac{n(1-D)+D}{n-D(1+n)}$ ....(9)

Now if simple boost control method is used in the trans ZSI topology then from eqn (9) 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

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

Peak of the output phase voltage

$$V_{ph} = MBV_{in}\frac{1}{2} = \frac{nM+1-M}{nM+M-1}V_{in}M\times\frac{1}{2}$$

In case of maximum boost control method, used in the trans ZSI topology then from eqn (9)

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

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

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

Switching stress

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

Peak of the output phase voltage

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

Now if Maximum constant boost control method is used in the Trans ZSI topology, the eqn (9) 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 $G = M\times\frac{2n + (1-n)(2 - \sqrt{3}M)}{2n - (1+n)(2\pi - \sqrt{3}M)}$

Switching stress

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

Peak of the output phase voltage

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

Again, from the above derivations, the voltage across the inductor are easily derived using switching function S_f and considering n=1.

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

$$=\frac{1}{1-2D}S_f-\frac{D}{1-2D}\,and$$

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

All the above mathematical expression derived as a function of modulation index (M) are duty cycle (D), boost factor (B), overall gain of the inverter(G) and the peak value of phase voltage (V_{ph}) available. The maximum possible modulation index $M_{\max}$ and voltage stress across switch are expressed in terms of gain G.

3. Results & Discussion

An extensive comparative study is carried out under MATLAB SIMULINK environment for all the z-source converters with three different modes of control strategies. The study is done based on its capability of delivering a constant three phase output voltage irrespective of parameters and shoot-through duty cycle but under a constant dc link input. The modulation index and switching frequency are not varied under this study. To keep output constant, the duty cycles are varied and circuit parameters are adjusted accordingly. To get smooth sinusoidal at the output, the filter size is also adjusted. Specifications are selected for the simulation work is as below: Source voltage, V_{in}=150 V, Modulation index, M=0.9 and Switching frequency, fs=10 kHz, Load resistance, R_L=5 ohms, Load inductance, L_L=2mH.
Twelve set of separate simulation have been performed based on four topologies and their three PWM control strategies and the results are presented in Table I.

It shows that tans-ZSI and trans-qZSI with a single capacitor have almost similar performance and specially constant boost control is the best among all the controls.

The size of L and C required are less in case of trans-ZSI and trans-qZSI but output contains more harmonics and therefore filter size increases.THD of output voltage without filter is presented in the table and that support the requirement of particular size of filter.

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. Conclusion

Three major types of switching pulse width modulation techniques for three recently proposed three phase voltage fed Z-source inverters (ZSI) topologies have been explored and compared. Comparison is done based on their capability of providing constant voltage at the output under variable input condition of a power system. The boost factor, voltage gain, duty ratio, and voltage stress across the switches for each method have been analyzed in detail. The mathematical expression of capacitor voltages, inductor currents and input currents are derived which are supported by simulated results. By comparing the performance of them, proper ZSI and proper switching control method can be selected for the application of power conditioner under different load types. Comparison of theoretical and simulation results will help to select the right topology of ZSI as well as type of PWM control method.

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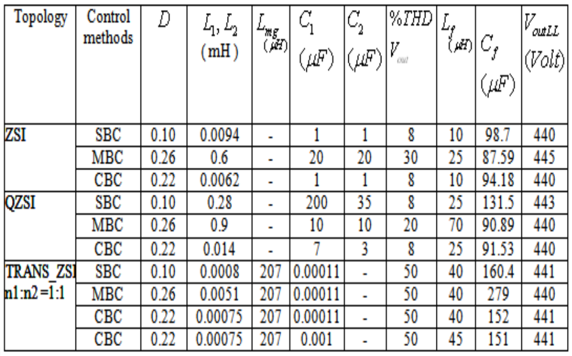
Table I: Results of different circuit parameters for different type of ZSI under different switching method



Topology	Control methods	D	L_1, L_2 (mH)	L_{mg} (μH)	C_1 (μF)	C_2 (μF)	%THD V_{out}	L_f (μH)	C_f (μF)	V_{outLL} (Volt)
ZSI	SBC	0.10	0.0094	-	1	1	8	10	98.7	440
	MBC	0.26	0.6	-	20	20	30	25	87.59	445
	CBC	0.22	0.0062	-	1	1	8	10	94.18	440
QZSI	SBC	0.10	0.28	-	200	35	8	25	131.5	443
	MBC	0.26	0.9	-	10	10	20	70	90.89	440
	CBC	0.22	0.014	-	7	3	8	25	91.53	440
TRANS_ZSI n1:n2 =1:1	SBC	0.10	0.0008	207	0.00011	-	50	40	160.4	441
	MBC	0.26	0.0051	207	0.00011	-	50	40	279	440
	CBC	0.22	0.00075	207	0.00011	-	50	40	152	441
	CBC	0.22	0.00075	207	0.001	-	50	45	151	441