

Analysis and Simulations of Z-Source Inverter Control Methods

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Abstract –In this paper, two different control methods for Z-source inverter are examined. The Simple Boost and the Maximum Boost control methods of the inverter are analyzed and compared each other using simulation with MATLAB/Simulink. The Simple Boost control with independence relation between modulation index and shoot-through duty ratio is also simulated and analyzed. The selection of high modulation index and shoot-through duty ratio can reduce the inverter's dc link voltage overshoot and increasing power delivery capacity of the inverter.

Keywords–Z-Source inverter; PWM; Control; Fuel Cell.

I. INTRODUCTION

Z-source inverter can boost dc input voltage with no requirement of dc-dc boost converter or step up transformer, hence overcoming output voltage limitation of traditional voltage source inverter as well as lower its cost. A comparison among conventional PWM inverter, dc-dc boosted PWM inverter, and Z-source inverter shows that Z-source inverter needs lowest semiconductors and control circuit cost, which are the main costs of a power electronics system [1]. This results in increasing attention on Z-source inverter, especially for the application where the input DC source has a wide voltage variation range, such as the photovoltaic (PV) grid-tied generation and fuel cell motor drive system [2]. Moreover, for Z-source inverter we have not to worry about EMI influence since shoot through are welcome and even exploited. This in turn enhances the inverter reliability.

There are various methods can be used to control Z-source inverter [3 – 9]. These can be classified into two categories according to the different shoot-through (ST) states insertion methods. The first category has the principle that ST states are generated by properly level shifting the modulation signals of voltage source inverter. ST states then will be inserted at every states transition, six ST state insertions in one switching cycle. The second category, in the other hand, directly replaces the

null states (111 and 000) by ST states. There are two ST states insertion in one switching cycle of the second category. The comparison of these two categories shows that the second category has higher efficiency than the first category [2]. In this paper, two different ways of Z-source inverter control with two ST states insertion in one switching cycle (second category) will be examined and compared through simulation by MATLAB/ Simulink.

II. Z-SOURCE INVERTER

The configuration of 3-phase Z-source inverter is shown in Fig. 1. It consists of 2 identical inductors and 2 identical capacitors which are composed to form a unique impedance network to avoid short circuit when the devices are in shoot through mode, a diode to block reverse current, and a three phase bridge as in traditional inverter. In 3-phase Z-source inverter, one additional control parameter is introduced, namely the Boost Factor (B), which modifies the AC output voltage equation of traditional 3-phase PWM inverter as following.

$$\hat{v}_{out} = BM \frac{V_o}{2} \quad (1)$$

Where:

\hat{v}_{out} = Maximum sinusoidal inverter output voltage

B = Boost factor

M = Modulation Index

V_o = DC Input voltage

If we replace BM with G, then we may rewrite (1) as

$$\hat{v}_{out} = G \frac{V_o}{2} \quad (2)$$

G is the inverter gain,

$$G = BM \quad (3)$$

It can be seen that (2) has the same form with that of the traditional VSI, i.e.

$$\hat{v}_{out} = M \frac{V_o}{2} \quad (4)$$

Boost Factor is obtained by introducing shoot through of minimally one pare of the inverter arm for a short period of time which called shoot-through time.

$$B = \frac{1}{1 - 2\frac{T_o}{T}} = \frac{1}{1 - 2D_o} \quad (5)$$

Where: T_o = Shoot Through Time
 T = Switching Period
 D_o = Shoot through Duty Ratio

Thus, in the 3-phase Z-source inverter we have 9 permissible switching states, unlike the traditional 3-phase V-source inverter that has eight. They comprise 6 active states, 2 zero states, and 1 additional zero state called shoot through zero states that is forbidden in traditional voltage source inverter.

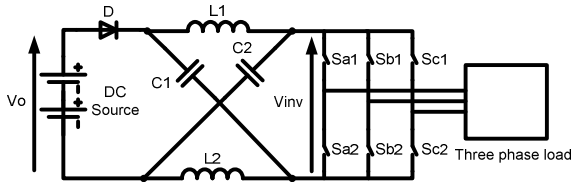


Figure 1. Three-Phase Z-Source Inverter

III. SIMPLE BOOST CONTROL METHODS

Actually, this control strategy inserts shoot through in all the PWM traditional zero states during one switching period. This maintains the six active states unchanged as in the traditional carrier based PWM. The simple boost control method is illustrated in Fig. 2. Two straight lines are employed to realize the shoot through duty ratio (D_o). The first one is equal to the peak value of the three-phase sinusoidal reference voltages while the other one is the negative of the first one. Whenever the triangular carrier signal is higher than the positive straight line or lower than the negative straight line,

the inverter will operate in shoot-through. Otherwise it works as a traditional PWM inverter. Fig. 2 shows the modulation, the driver signals for the six switches, and the ST signals of simple boost control method. Since the value of the positive straight line equals to the maximum of the sinusoidal reference signals and the value of the negative straight line equals to the minimum of the sinusoidal reference signal, then the modulation index (M) and the shoot-through duty ratio (D_o) are interdependence each other. The relation between these two parameters is expressed in equation (6). We can see from the equation that shoot-through duty ratio (D_o) decreases with increasing modulation index (M).

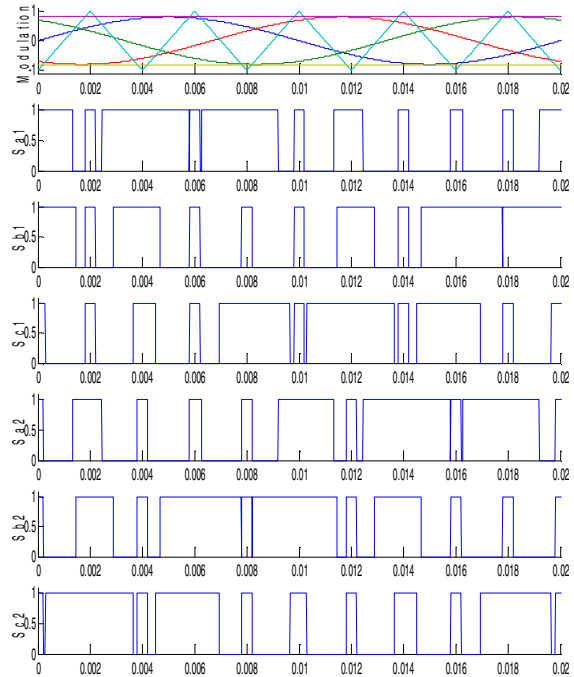


Figure 2. PWM signal of simple boost control

$$D_o = 1 - M \quad (6)$$

From (3) and (5) we get

$$G = BM = \frac{M}{1 - 2D_o} \quad (7)$$

Since $D_o = 1 - M$, thus

$$G = \frac{M}{1 - 2D_o} = \frac{M}{1 - 2(1 - M)} = \frac{M}{2M - 1} \quad (8)$$

Equation (8) infers that the inverter gain (G) can be controlled by adjusting modulation index (M). If we rearrange (1) in the original PWM output voltage equation form, we get

$$\hat{v}_{out} = M \frac{BV_o}{2} \quad (9)$$

BV_o should be the dc input voltage of the traditional VSI which in the case of Z-source inverter is the dc voltage applied to inverter bridge.

Say

$$BV_o = V_{inv} \quad (10)$$

It can be seen from Fig. 1 that V_{inv} is the voltage stress of the inverter's devices.

From (3) and (8),

$$B = 2G - 1 \quad (11)$$

Substitute (11) to (10), the voltage stress across the devices is

$$V_{inv} = (2G - 1)V_o = \frac{1}{2M - 1}V_o \quad (12)$$

IV. MAXIMUM BOOST CONTROL METHOD

Maximum boost control method converts all traditional zero states to shoot-through while maintaining the six active states remain unchanged. This is obtained by comparing the maximum and the minimum curve of the sinusoidal reference with the triangular carrier. Whenever the maximum is lower than the triangular or the minimum is higher than the triangular, the inverter shoots through. Otherwise, it operates in the traditional PWM mode. By this control strategy the shoot-through duty cycle varies each cycle. The inverter gains maximum shoot-through time which in turn gives the inverter higher boost factor, according to equation 5. Thus, with the same modulation index as in simple boost control method, we get higher voltage gain. Fig. 3 shows the maximum boost control strategy.

As the shoot-through duty cycle varies each cycle, what we are interested in is the average value of the duty cycle. In the interval $(\pi/6, \pi/2)$, the average shoot through duty ratio can be expressed as following.

$$\begin{aligned} \frac{\bar{T}_o}{T} &= \frac{\int_{\pi/6}^{\pi/2} (2 - M \sin \theta - M \sin(\theta - 2\pi/3)) d\theta}{2} \\ &= \frac{2\pi - 3\sqrt{3}\pi}{2\pi} \end{aligned} \quad (13)$$

From (5) and (13),

$$B = \frac{1}{1 - 2\frac{\bar{T}_o}{T}} = \frac{\pi}{3\sqrt{3}M - \pi} \quad (14)$$

The inverter voltage gain (G) is obtained as

$$G = BM = \frac{\pi}{3\sqrt{3}M - \pi} M = \frac{\pi M}{3\sqrt{3}M - \pi} \quad (15)$$

Again, as with the simple boost control method, the voltage gain can be controlled by adjusting the modulation index.

Fig. 4 shows voltage gain as the function of modulation index for both simple boost and maximum boost control methods. It is clear from the figure that maximum boost control method gives higher voltage gain for the same modulation index.

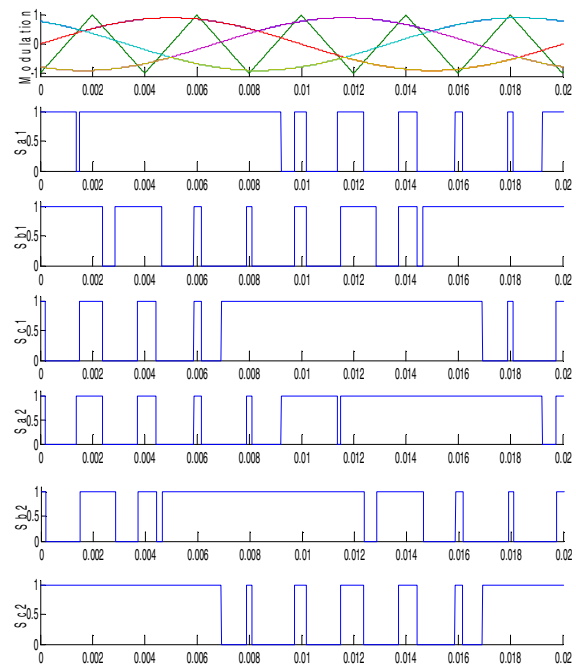


Figure 3. PWM signal of maximum boost control

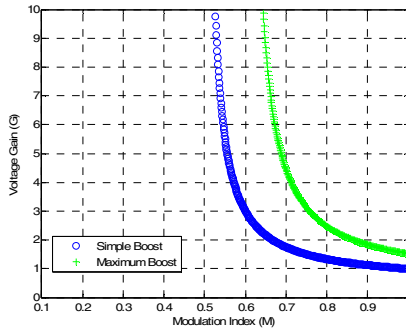


Figure 4. Voltage Gain versus Modulation Index

Obviously, the voltage stress across the inverter's devices is

$$V_{inv} = BV_o = \frac{\pi}{3\sqrt{3}M - \pi} V_o \quad (16)$$

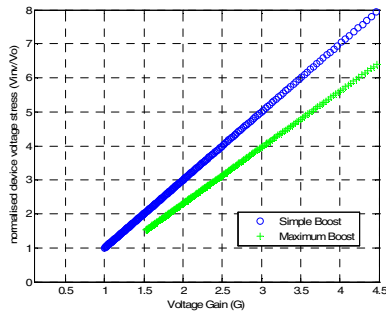


Figure 5. Devices Voltage Stress

The voltage stress across the devices in obtaining a specified voltage gain for both the simple boost and the maximum boost control method is depicted in Fig. 5. From the figure, it is shown that the maximum boost control method can reduce the voltage stress across the inverter's devices for the same voltage gain compared with the simple boost control. It means that for given devices, the inverter can obtain higher voltage gain.

V. OPERATION OF Z-SOURCE INVERTER UNDER SIMPLE BOOST CONTROL METHOD WITH INDEPENDENT RELATIONSHIP BETWEEN THE MODULATION INDEX (M) AND THE SHOOT THROUGH DUTY RATIO (D_o)

As was previously discussed, usually the simple boost control method is achieved by using a pair of straight line which are equal to the maximum peak and minimum peak of the reference sinusoidal, implying that the modulation index (M) and the shoot through duty ratio are related each other. The relationship is expressed by (6) as $D_o = 1 - M$. In the rest of this paper, simulation of simple boost operation of z-source

inverter whose modulation index and shoot-through duty ratio are independent of each other is carried out. This control strategy is done by setting the straight lines unequal to the peak maximum and minimum of the sinusoidal reference signals. Simulation is conducted using various values of shoot-through duty ratio (D_o) and modulation index (M). The straight line value is normalized by the peak value of the triangular carrier wave. Initially, simulation is conducted by M equals 1.0 and D_o equals 0.45. Then simulation is carried on with M equals 0.9, 0.55, and 0.4 while D_o remains at the same value.

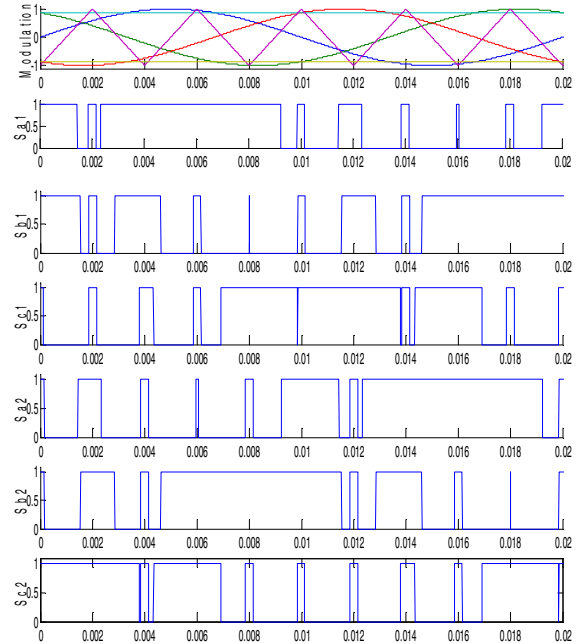
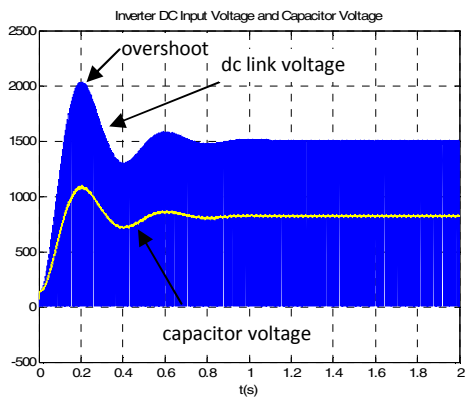
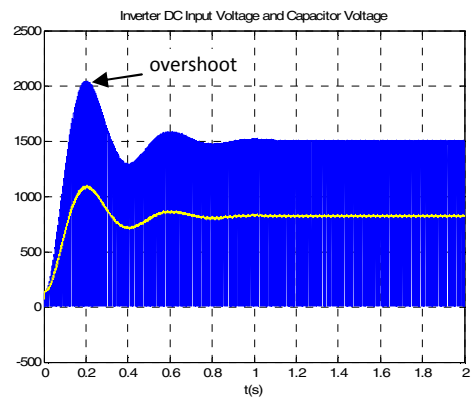


Figure 6. PWM signal of simple boost control with independent relationship between modulation index and shoot-through duty ratio

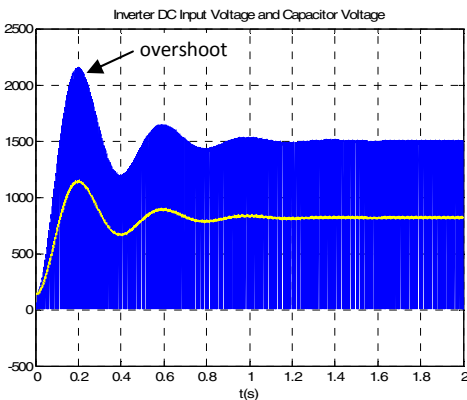
The simulation results will be discussed in the following part. Fig. 7 shows the inverter's dc link voltage and the Z network's capacitor voltage. We observe from the figure that the inverter builds equal steady state dc link voltage (V_{inv}) and capacitor voltage. However, there are variations in the value of voltage overshoot of the dc link voltage. As can be seen from Fig. 7, the lowest overshoot occurs when the modulation index and shoot-through duty ratio are high (Fig. 7a : $M = 1.0$, $D_o = 0.45$). Meanwhile, Fig. 8 shows the inverter's ac output voltage and output current resulted from the simulation. It can be seen that the output voltage of the inverter are the same for all the conditions carried out through the simulation. Variation is observed in the output current delivered by the inverter. It is shown in Fig. 8 that the inverter delivers the highest output current when the modulation index is much higher than the straight line (Fig. 8a : $M = 1.0$, $D_o = 0.45$). Since the output



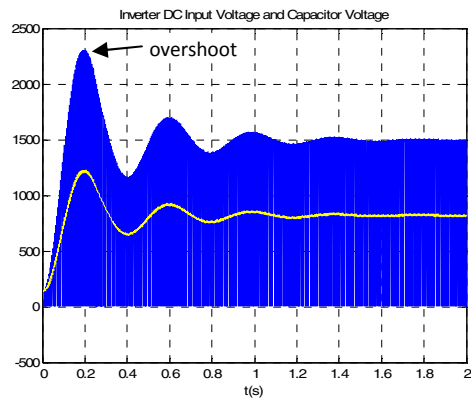
(a)



(b)

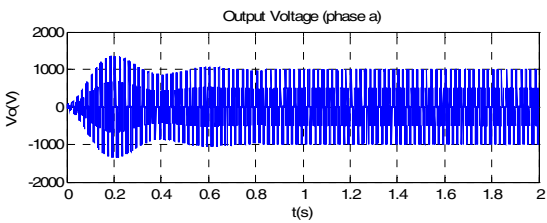


(c)

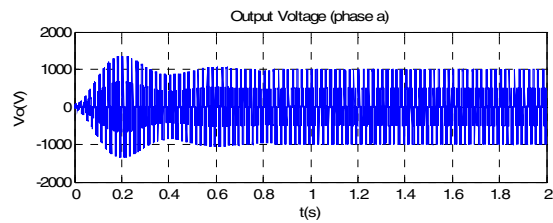


(d)

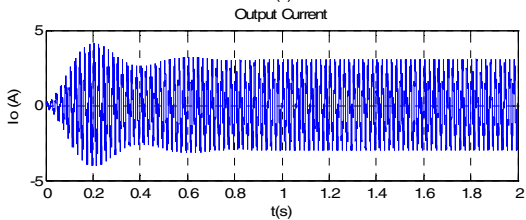
Figure 7. Inverter dc input voltage and capacitor voltage at various Modulation Index and Shoot-through Duty Ratio : (a) $M = 1.0$, $D_0 = 0.45$, (b) $M = 0.9$, $D_0 = 0.45$, (c) $M = 0.55$, $D_0 = 0.45$ (d) $M = 0.4$, $D_0 = 0.45$



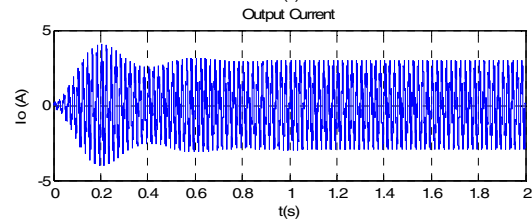
(a)



(c)



(a)



(c)

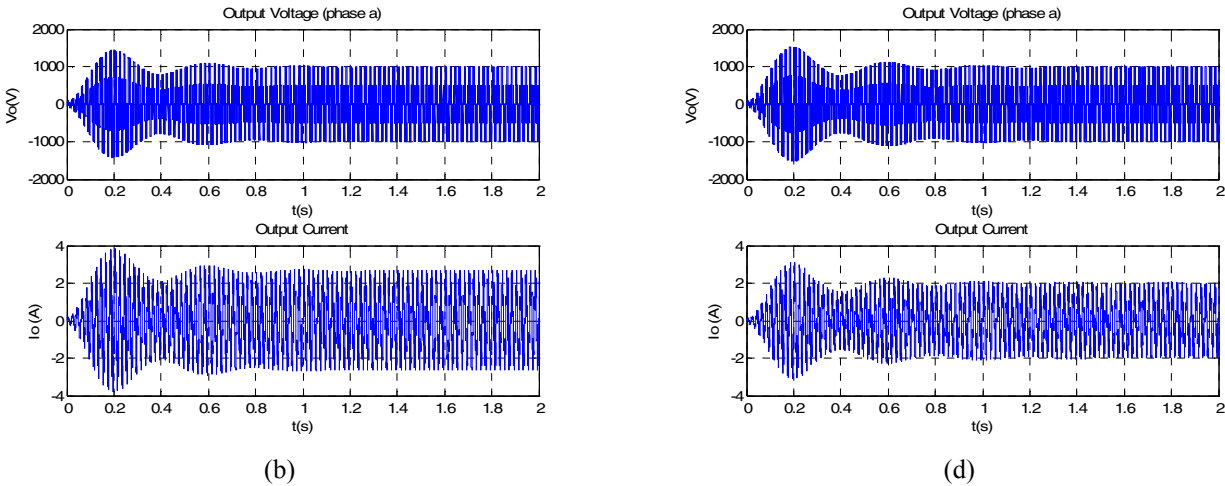


Figure 8. Output voltage and output current at various Modulation Index and Shoot-through Duty Ratio (a) $M = 1.0$, $D_0 = 0.45$, (b) $M = 0.9$, $D_0 = 0.45$, (c) $M = 0.55$, $D_0 = 0.45$ (d) $M = 0.4$, $D_0 = 0.45$

voltages are equal, higher output current of the inverter means higher output power. Hence, according to the simulation results, for simple boost control of z-source inverter, it would be more advantageous to use high modulation index and high shoot-through duty ratio as the inverter would deliver higher output power with lower inverter's dc input voltage overshoot.

CONCLUSION

Two control methods with two ST states insertion of Z-source inverter has been analyzed and compared in this paper. The boost factor, voltage gain, duty ratio, and voltage stress across the switches for each method have been analyzed in detail. Simulation of Z-source converter under simple control method using straight lines with the value different from the peak value of the sinusoidal reference has also been presented, showing that better performance would be obtained if modulation index (M) and shoot-through duty ratio (D_0) are set to a high value.

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