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Designing of Impedance Network of Z-Source Inverter for Different Control Methods

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ABSTRACT
In this paper, designing of impedance network of Z-source inverter is done for different control methods. The values of inductor and capacitors are calculated for Simple boost control, Maximum boost control and maximum constant boost control method of Z-source inverter for the same modulation index. The simulation is performed and the results are shown using MATLAB/Simulink.

Keywords—Boost factor, Modulation index, PWM, Shoot-through duty ratio, Z-source inverter

I. INTRODUCTION

The Z-source inverter has introduced [1] which can boost the d.c input voltage without using any dc-dc boost converter or step up transformer, hence overcoming the limitations of traditional inverters. The 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 [2]. This results in increasing attention on Z-source inverter, especially for the application where the input DC source has a wide voltage range, such as fuel cell motor drive system and the photovoltaic (PV) grid-tied generation. Also, in Z-source inverter, there is no EMI influence since it can have shoot-through state. This in turn enhances the inverter reliability.

There are various methods that can be used to control the Z-source inverter [3-4]. These controlling methods are classified according to the insertion of the shoot-through (ST) states. These methods are:

i) Simple Boost Control
ii) Maximum Boost Control
iii) Maximum Constant Boost Control

In this paper, the values of capacitors and inductors are calculated forming an impedance network for all the controlling methods. The outputs are analysed by simulation using MATLAB/Simulink.

II. Z-SOURCE INVERTER

The configuration of a 3-phase Z-source inverter is shown in Fig. 1. It consists of 2 inductors of same inductance and 2 capacitors of the same capacitance which collectively form a unique impedance network to avoid short circuit when the devices are in the shoot-through state, a diode to block the reverse current, and a 3-phase bridge as in traditional inverter.

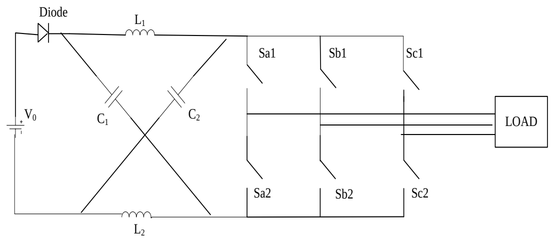

Fig.1. Circuit diagram of a 3-phase Z-source inverter

An additional parameter is introduced in Z-source inverter namely the Boost Factor (B), which modifies the output AC voltage as following:

$$\hat{v}_{ac} = M.B.\frac{V_0}{2} \quad (1)$$

Where,
$\hat{v}_{ac}$ = Maximum sinusoidal inverter output voltage
B = Boost Factor
M = Modulation Index
V_0 = DC input voltage

If we replace M.B with G, then we may rewrite the above equation as

$$\hat{v}_{ac} = G.\frac{V_0}{2} \quad (2)$$

G is the inverter gain,

$$G = M.B \quad (3)$$

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

$$\hat{v}_{ac} = M.\frac{V_0}{2} \quad (4)$$

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

$$B = \frac{1}{1 - 2\frac{T_0}{T}} = \frac{1}{1 - 2D} \quad (5)$$

Where, D = Shoot through duty ratio

The 3-phase Z-source inverter has nine permissible switching states unlike the traditional 3-phase voltage source inverter that has eight. It comprises of 6 active states, 2 zero states, and an additional zero state called as shoot through zero state that is forbidden in traditional V-source inverter.

There are different control strategies to insert shoot through in all PWM traditional zero states during one switching period while maintaining the six active states unchanged.

III. DESIGNING OF IMPEDANCE NETWORK

The switching equivalent is given for Z-source inverter in fig.2.

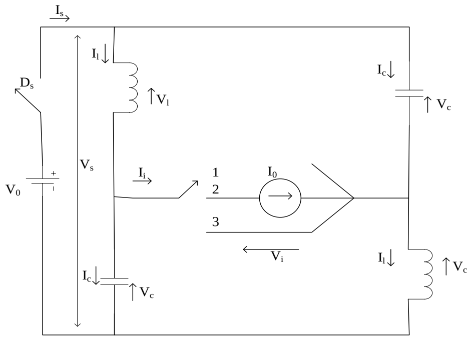

Fig.2. Switching equivalent of ZSI

Let, V_l and I_l are the voltage and current through the inductor. V_c and I_c are the voltage and current through the capacitor. V_s and I_s are the voltage and current at the input terminals of the impedance network and V_i and I_i are the voltage and current at input terminals of the inverter.To analyse the voltage-current variations in each of the possible states [5], the common equations that describe the impedance network in general can be written as:

$$V_l = L(dI_l/dt) \quad , I_c = C(dV_c/dt) \qquad (6)$$
$$V_s = V_c + V_l \quad , I_s = I_c + I_l \qquad (7)$$
$$V_i = V_c - V_l \quad , I_i = I_l - I_c \qquad (8)$$

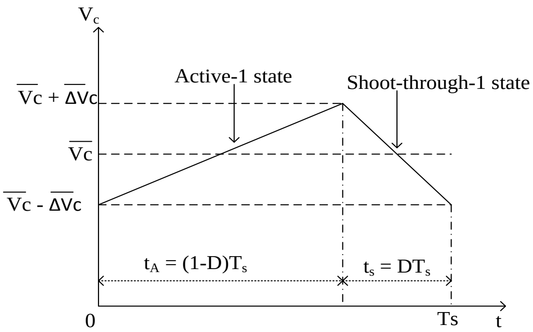

Fig.3.Waveform of capacitor voltage

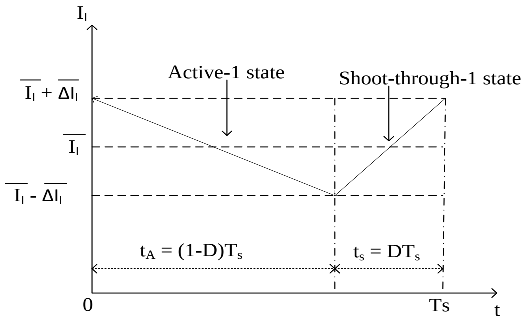

Fig.4. Waveform of inductor current

Fig.3 and fig.4 shows the linear waveforms of the capacitor voltage and inductor current respectively for one switching cycle of the dc link.

By taking peak ripples and average values of capacitor voltage and inductor current as ΔV_c, $\overline{V_c}, \Delta I_l$, and respectively, the maximum and minimum values of the two variables can be written as:

$$V_{min} = \overline{V_c} - \Delta V_c = (1 - k_v)\overline{V_c}$$
$$I_{min} = \overline{I_l} - \Delta I_l = (1 - k_l)\overline{I_l} \qquad (9)$$
$$V_{max} = \overline{V_c} + \Delta V_c = (1 + k_v)\overline{V_c}$$
$$I_{max} = \overline{I_l} + \Delta I_l = (1 + k_l)\overline{I_l} \qquad (10)$$

Where, $k_v = \Delta V_c/\overline{V_c}$ and $k_l = \Delta I_l/\overline{I_l}$ are the ripple factors of the two waveforms.

With linear waveforms and from eq.(6), ΔV_c and ΔI_l can be expressed as:

$$\Delta V_c = \frac{\overline{I_c}\Delta t}{C} \quad ; \quad \Delta I_l = \frac{\overline{V_l}\Delta t}{L} \qquad (11)$$

Considering shoot-through-1 period, where $I_s = 0$ and $V_i = 0$,

$$C = \frac{\overline{I_l}DT_s}{2\Delta V_c} \quad ; \quad L = \frac{\overline{V_c}DT_s}{2\Delta I_l} \qquad (12)$$

Since average inductor voltage and capacitor current over complete switching cycle in steady state are zero.

$$\overline{V_c}/V_0 = \overline{I_l}/I_0 = \lambda \qquad (13)$$

Where, $\lambda = \frac{1-D}{1-2D}$

Combining eq.(11) and (12),

$$C = \frac{I_0 DT_s}{2k_c V_0} \quad ; \quad L = \frac{V_0 DT_s}{2k_l I_0} \qquad (14)$$

Where,

$$I_0 = \frac{3}{4}\frac{M I_m \cos\emptyset}{(1 - D)}$$

Thus, substituting I_o in eq.(14)

$$C = \frac{3DT_s M I_m \cos\emptyset}{8k_c V_0(1 - D)} \; ; \quad L = \frac{2V_0 DT_s(1 - D)}{3k_l M I_m \cos\emptyset} \qquad (15)$$

Thus if d.c input voltage (V_0), switching period (T_s), Modulation index (M), maximum load current (I_m), and power factor are known, the values of capacitors and inductors can be calculated for any control strategy.

IV. SIMPLE BOOST CONTROL METHOD

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.In this method, two straight lines are employed to realize the shoot through duty ratio (D). One of them is equal to the peak value of the 3 phase sinusoidal reference voltages while the other 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 the shoot through state. Else, it works as a traditional PWM inverter. Since the value of the positive straight line is equal to the maximum of sinusoidal reference signal, the modulation index (M) and shoot through duty ratio (D) are interdependence each other. The relation between the two is as follows:

$$D = 1 - M \qquad (16)$$

Therefore, from (5),

$$B = \frac{1}{2M - 1} \qquad (17)$$

$$G = BM = \frac{M}{1 - 2D} \qquad (18)$$

Thus,

$$G = \frac{M}{2M - 1} \qquad (19)$$

The simple boost control method is illustrated in fig.5.

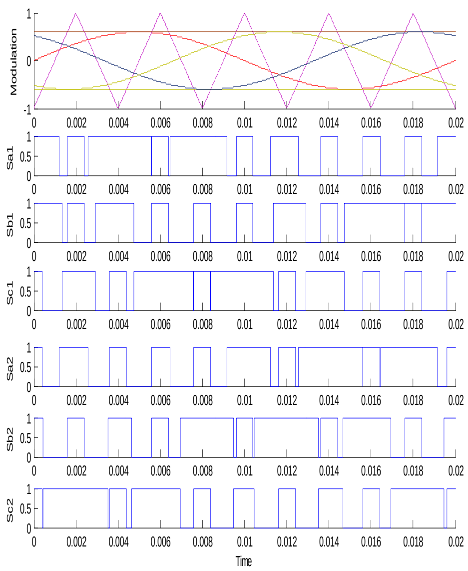

Fig5. PWM signal of Simple Boost Control

Thus, substituting in eq.(15),

$$C = \frac{3(1 - M)T_s I_m \cos\emptyset}{8 k_v V_0} \qquad (20)$$

$$L = \frac{2V_0(1 - M)T_s}{3 k_i I_m \cos\emptyset} \qquad (21)$$

V. MAXIMUM BOOST CONTROL METHOD

This control strategy converts all the traditional zero states to the shoot-through while maintaining the six active states remain unchanged as in the simple boost control. But this is obtained by comparing the maximum and the minimum curve of the sinusoidal reference with the triangular carrier signal. When the maximum is lower than the triangular or the minimum is higher than the triangular, the shoot through is there. Else, it operates in the PWM mode. By this control strategy, the shoot through duty cycle varies each cycle. The inverter gains maximum shoot-through time which gives the higher boost factor according to equation (5). Therefore, for the same modulation index, we get the higher voltage gain as compared to the simple boost control.In maximum boost control, the relationship between modulation index, M and shoot-through duty ratio, D is

$$D = 1 - \frac{3\sqrt{3}M}{2\pi} \qquad (22)$$

Thus,

$$B = \frac{\pi}{3\sqrt{3}M - \pi} \qquad (23)$$

The inverter voltage gain (G) is obtained as

$$G = BM = \frac{\pi M}{3\sqrt{3}M - \pi} \qquad (24)$$

The maximum boost control method is illustrated in fig.6.

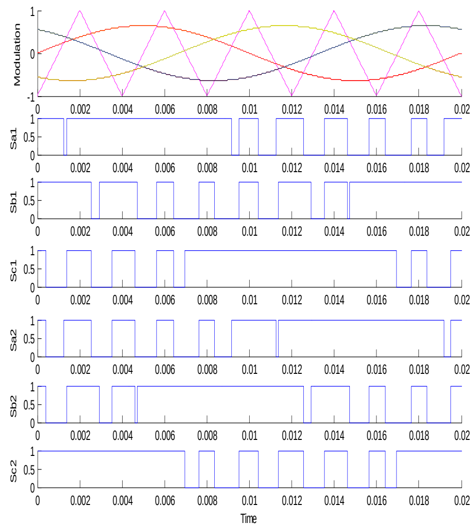

Fig.6. PWM signal of Maximum Boost Control

By substituting in eq.(15), we get

$$C = \frac{(2\pi - 3\sqrt{3}M)T_s I_m \cos\emptyset}{8 k_v V_0} \qquad (25)$$

$$L = \frac{\sqrt{3}V_0(2\pi - 3\sqrt{3}M)T_s}{2\pi^2 k_i I_m \cos\emptyset} \qquad (26)$$

VI. MAXIMUM CONSTANT BOOST CONTROL METHOD

In order to reduce the volume and cost, it is always important to keep the shoot-through duty ratio constant. At the same time, a greater voltage boost for any given modulation index is desired to reduce the voltage stress across the switches. There are five modulation curves in this control method: three reference signals, *Va*, *Vb*, and *Vc*, and two shoot-through envelope signals, *Vp* and *Vn*. When the carrier triangle wave is greater than the upper shoot-through envelope, *Vp*, or lower than the lower shoot-through envelope, *Vn*, the inverter is turned to a shoot-through zero state. In between, the inverter switches in the same way as in traditional carrier-based PWM control. Because the boost factor is determined by the shoot-though duty cycle, as expressed in (5), the shoot-through duty cycle must be kept the same in order to maintain a constant boost. The basic point is to get the maximum *B* while keeping it constant all the time.
The shoot through duty ratio is maintained constant and expressed as:

$$D = 1 - \frac{\sqrt{3}M}{2} \qquad (27)$$

Thus, the boost factor and the voltage gain can be calculated as:

$$B = \frac{1}{1-2D} = \frac{1}{\sqrt{3}M - 1} \qquad (28)$$

And,

$$G = BM = \frac{M}{\sqrt{3}M - 1} \qquad (29)$$

This method of maximum constant boost control is implemented by injecting third harmonic [4]. This method is illustrated in fig.7.

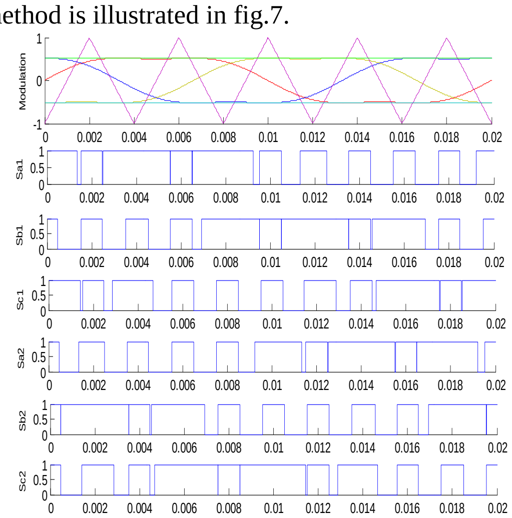

Fig.7. PWM signal of Maximum Constant Boost Control

By substituting in eq.(15), we get

$$C = \frac{3(2-\sqrt{3}M)T_s I_m \cos\emptyset}{8\sqrt{3}k_v V_0} \qquad (30)$$

$$L = \frac{V_0(2-\sqrt{3}M)T_s}{2\sqrt{3}k_i I_m \cos\emptyset} \qquad (31)$$

VII. SIMULATION RESULTS

Simulations have been performed to confirm the above analysis. For the same values of input d.c voltage, switching frequency, modulation index, power factor and load current, the simulation is done for all the controlling methods. The parameters taken are:

TABLE I: PARAMETERS FOR THE SIMULATION

Parameters	**Values**
Input D.C voltage(V)	20
Load current(A)	5
Power factor	0.8
Switching frequency(kHz)	4
Modulation Index	0.65
Ripple factor, k_v and k_i	0.05

From the above parameters,
The maximum load current, $I_m = 5 \times \sqrt{2} = 7.07$
Switching period, $T_s = 1/f_s = 1/4000 = 2.5 \times 10^{-}$

A. Simple Boost Control

From the eq.(20) and (21),

$$C = \frac{3 \times (1-0.65) \times 2.5 \times 10^{-4} \times 7.071 \times 0.8}{8 \times 0.05 \times 20} = 185.6\mu F$$

$$L = \frac{2 \times 20 \times (1-0.65) \times 2.5 \times 10^{-4}}{3 \times 0.05 \times 7.071 \times 0.8} = 4.124mH$$

Using the above values of capacitor and inductor for the Z-source inverter, the simulation has been done.
Fig.8 shows the simulation results for DC link voltage, inductor current, line voltage and load current using MATLAB/Simulink.

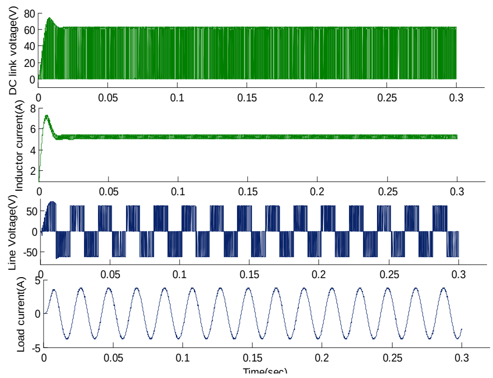

Fig.8. Simulation waveforms of SBC method

Theoritically,

$$B = \frac{1}{1-2(1-M)} = 3.33$$

$$\hat{v}_{ac} = M.B.\frac{V_0}{2} = 0.65\ .3.33.\frac{20}{2} = 21.64V$$

B. Maximum Boost Control

From eq.(25) and (26),

$$C = \frac{(2\pi - 3\sqrt{3}(0.65)) \times 2.5 \times 10^{-4} \times 7.071 \times 0.8}{8\sqrt{3} \times 0.05 \times 20} = 296.5\mu F$$

$$L = \frac{\sqrt{3} \times 20(2\pi - 3\sqrt{3}(0.65)) \times 2.5 \times 10^{-4}}{2\pi^2 \times 0.05 \times 7.071 \times 0.8} = 4.507mH$$

By taking the above values of capacitor and inductor, the simulation is done. Fig.9 shows the simulation results for DC link voltage, inductor current, line voltage and load current using MATLAB/Simulink.

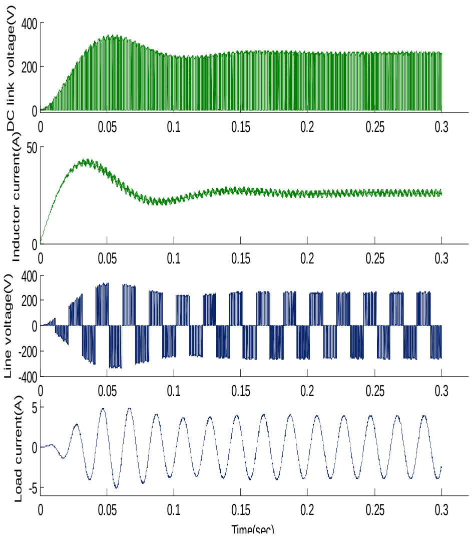

Fig.9. Simulation waveforms of MBC method

And theoretically,

$$B = \frac{\pi}{3\sqrt{3}M - \pi} = 13.317$$

$$\hat{v}_{ac} = M.B.\frac{V_0}{2} = 0.65\ .13.317\ .\frac{20}{2} = 86.56V$$

C. Maximum Constant Boost Control

From eq. (30) and (31),

$$C = \frac{3(2-\sqrt{3}(0.65)) \times 2.5 \times 10^{-4} \times 7.071 \times 0.8}{8\sqrt{3} \times 0.05 \times 20} = 267.6\mu F$$

$$L = \frac{20(2-\sqrt{3}(0.65)) \times 2.5 \times 10^{-4}}{2\sqrt{3} \times 0.05 \times 7.071 \times 0.8} = 4.46mH$$

By taking the above values of capacitor and inductor, the simulation has been done. Fig.10 shows the simulation results for DC link voltage, inductor current, line voltage and load current using MATLAB/Simulink.

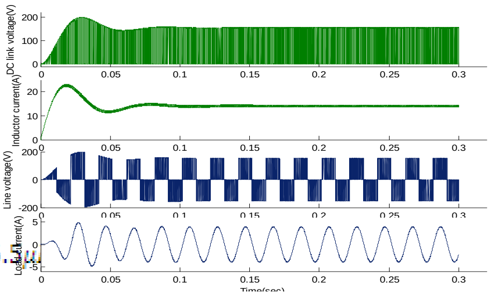

Fig.10. Simulation waveforms of MCBC method

Theoretically,

$$B = \frac{1}{\sqrt{3}M - 1} = 7.947$$

$$\hat{v}_{ac} = M.B.\frac{V_0}{2} = 0.65\ .7.947\ .\frac{20}{2} = 51.65V$$

Through these waveforms, the theoretical calculations and simulation results can be compared and the validity can be confirmed.

VIII. CONCLUSION

The values of capacitors and inductors are calculated for the same input voltage, modulation index, switching frequency, load current and power factor for all the three controlling methods of the Z-source inverter. The simulation has been done using MATLAB/Simulink. The analytical and simulation results are compared and presented.

IX. ACKNOWLEDGEMENTS

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