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Z-SOURCE INVERTER WITH A NEW SPACE VECTOR PWM ALGORITHM FOR HIGH VOLTAGE GAIN

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ABSTRACT

This paper presents a methodology to apply a novel space vector pulse width modulation control for three phase Z-source inverter. The space vector modulation for the conventional voltage source inverter is modified so that the additional shoot-through states are inserted within the zero states. So zero voltage time period is diminished for generating a shoot-through time, and active states are unchanged. The shoot-through states are evenly distributed to each phase within zero state. The shoot-through time is used for controlling the dc link voltage boost and hence the output voltage boost of the inverter. This new method provides a high voltage gain at higher modulation index. The proposed algorithm is verified with simulation and experiment. MatLab/Simulink is used for simulating the complete circuit with RL load. The frequency spectra of the output voltage and current are explored.

Keywords: voltage gain, Z-source inverter, space vector PWM, current source inverter, total harmonic distortion.

Nomenclature:

a = Modulation index
CSI = Current source inverter
D = Shoot-through duty ratio
SVPWM = Space vector pulse width modulation
T_s = Switching time
T_1 = Switching time duration of V_1 at sector-1
T_2 = Switching time duration of V_2 at sector-1
T_0 = Switching time duration of zero vector
T_{st} = Shoot-through time period
THD = Total harmonic distortion
VSI = Voltage source inverter
V_1 to V_6 = Active vectors
V_0 and V_7 = Zero vectors
V_{ref} = Reference voltage vector
V_s = Input DC voltage
ZSI = Z-source inverter

1. INTRODUCTION

Traditional voltage-source inverter (VSI) and current source inverter (CSI) are either a buck or a boost converter and not a buck-boost converter. That is, their obtainable output voltage range is limited to either greater or smaller than the input voltage. Z-source inverter (ZSI) was proposed as an alternative power conversion concept as it can have both voltage buck and boost capabilities [1]. In addition to that it has the following advantages: Immune to EMI noise and mis-gating, low or no in-rush current compared with the voltage source inverter and low common mode noise. Figure-1 shows the main circuit of the Z-source inverter. It employs a unique impedance network coupled between the power source and the converter circuit that consists of a split-inductor L_1 and L_2 and capacitors C_1 and C_2 connected in X shape. The X-arms couple the inverter to a DC voltage source. The voltage source may be a battery, a diode rectifier or a fuel cell. This unique impedance network allows the Z-source inverter to buck or boost its output voltage, and also provides it with unique featuers that cannot be achieved in traditional power inverters.

Many pulse-width modulation (PWM) control methods have been developed and used for the traditional three phase voltage source inverter [2]. The traditional VSI 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 the lower or upper three devices. These total eight switching states and their combinations have spawned many PWM control schemes. On the other hand, Z-source inverter has additional zero vectors or shoot-through switching states that are forbidden in the traditional VSI, both switches of any phase leg can never be gated on at the same time or a short circuit (shoot through) would occur and destroy the inverter. The new Z-source inverter (ZSI) advantageously utilizes the shoot through state to boost the dc bus voltage by gating on both upper and lower switches of a phase leg and produce a desired output voltage that is greater than the available dc bus voltage. In addition the reliability of the inverter is greatly improved because the shoot-through due to misgating can no longer destroy the circuit. Thus it provides a low-cost, reliable, and high efficiency single stage structure for buck and boost power conversion. The operation principle and the shoot through duty ratio control using simple boost control method have been described in detail.

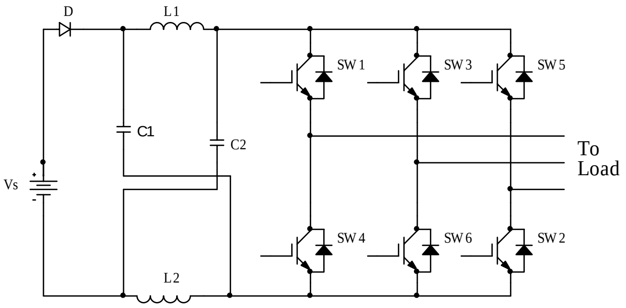

Figure-1. Z-Source inverter.

2. CARRIER BASED PWM METHODS

For an output voltage boost to be obtained, a shoot-through state should always be followed by an active state, i.e., shoot through states should be incorporated without affecting the active states. Thus, minor modifications in the traditional three phase sinusoidal PWM technique will yield various PWM control strategies for the ZSI. There are three available PWM control strategies for ZSI. They are simple boost control, maximum boost control, and maximum constant boost control methods.

The simple boost control method employs two straight envelops equal to or greater than the peak value of the three phase sinusoidal reference signals to control shoot-through duty ratio in a traditional sinusoidal PWM. The circuit is in shoot through state when the high frequency triangular carrier is greater than the upper straight line envelope or lesser than the lower straight line envelope. In this method the voltage stress across the switches is quite high, which restrict the obtainable voltage gain because of the limitation of device voltage rating. As during shoot through all the switches are ON, switching losses are high [1].

The maximum boost control is quite similar to the traditional carrier-based PWM control method, but this control method maintains the six active states unchanged and turns all zero states into shoot through zero states. The circuit is in shoot through state when the triangular carrier wave is greater than the maximum curve of the reference or lesser than the minimum curve of the reference. This method turns all the zero states into shoot through state thus minimizing the voltage stress across the switches. However it causes shoot through duty ratio to vary in each cycle, thus increasing the ripple content in inductor current. When the output frequency is low, the inductor ripple becomes significant and a large inductor is required. This increases the cost and size of the circuit [4].

In maximum constant boost control method the straight envelops of simple boost control method are replaced by two sinusoidal signals of three times the frequency of sinusoidal modulating signals. Thus this method involves three reference sinusoidal signals and two shoot through envelopes. The circuit enters shoot through state whenever the high frequency triangular wave is greater than the upper shoot-through envelope or lesser than the lower shoot-through envelope. This method achieves maximum boost while keeping shoot through duty ratio constant all the time, thus reducing ripple content in inductor current [5].

3. PROPOSED SPACE VECTOR PWM METHOD

Space vector PWM (SVPWM) in three phase voltage source inverters offers improved DC link voltage and reduced harmonic distortion, and has been therefore recognized as the preferred PWM method, especially in the case of digital implementation. The output voltage control by SVPWM consists of switching between the two active and one zero voltage vector in such a way that the time average within each switching cycle corresponds to the voltage command. In order to apply this concept for Z-source inverter, a novel modified SVPWM is needed to introduce the shoot-through states into the zero vectors without compromising the active states. Switching states for a conventional SVPWM is shown in Figure-2.

For a voltage source inverter the SVPWM can be implemented with the following algorithm.
The modulation index is

$$a = \frac{V_{ref}}{\frac{2}{3}V_s} \qquad (1)$$

Switching time durations for active states are

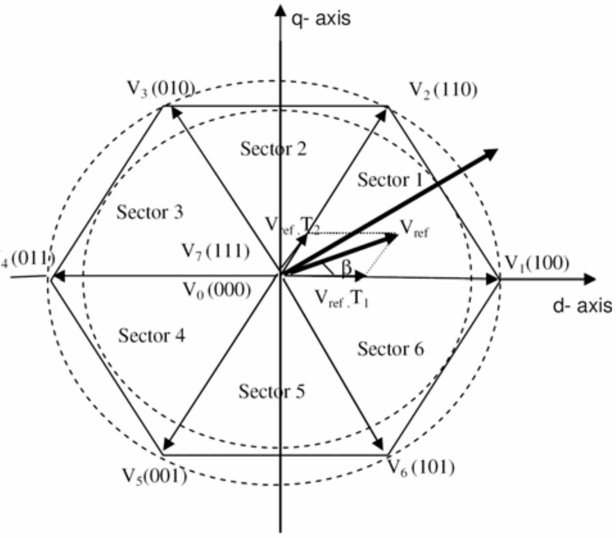

Figure-2. Voltage vector through conventional SVPWM of VSI.

$$T_1 = \frac{T_s.a.\sin(\frac{\pi}{3} - \beta)}{\sin(\frac{\pi}{3})} \qquad (2)$$

and

$$T_2 = \frac{T_s.a.\sin(\beta)}{\sin(\frac{\pi}{3})} \qquad (3)$$

Switching time duration for zero state is

$$T_0 = T_s - (T_1 + T_2) \qquad (4)$$

The SVPWM is suitable to control the output voltage of the Z-source inverter also. But to obtain the voltage boost at the output stage, the shoot-through states are required to be inserted. These shoot-through states will be distributed evenly into the switching period. These states will not change the active vectors in SVPWM algorithm since the shoot-through states and zero states in conventional SVPWM appears the same to the ac side by shorting the inverter three phase output terminals. In conventional SVPWM applied to VSI, the AC voltage vector is limited. That means the AC voltage vector is not available when the magnitude of required voltage beyond the limit imposed by conventional VSI, as indicated by Figure-2. However, with the proper shoot-through distribution within zero vectors, i.e., the proposed modified SVPWM for ZSI, any AC voltage beyond $2V_s/\pi$ could be implemented. The voltage vector through the modified SVPWM is shown in Figure-3. The PWM switching pattern for three phase Z-source inverter in sector-1 is shown in Figure-4. The shoot-through duty ratio which controls the boosted DC link voltage is:

$$D = \frac{4.T_{st}}{T_s} \tag{5}$$

In this pattern, the shoot-through period can be varied from 0 to $T_o/4$. So in one switching cycle the maximum shoot-through is increased to the zero state time T_o .

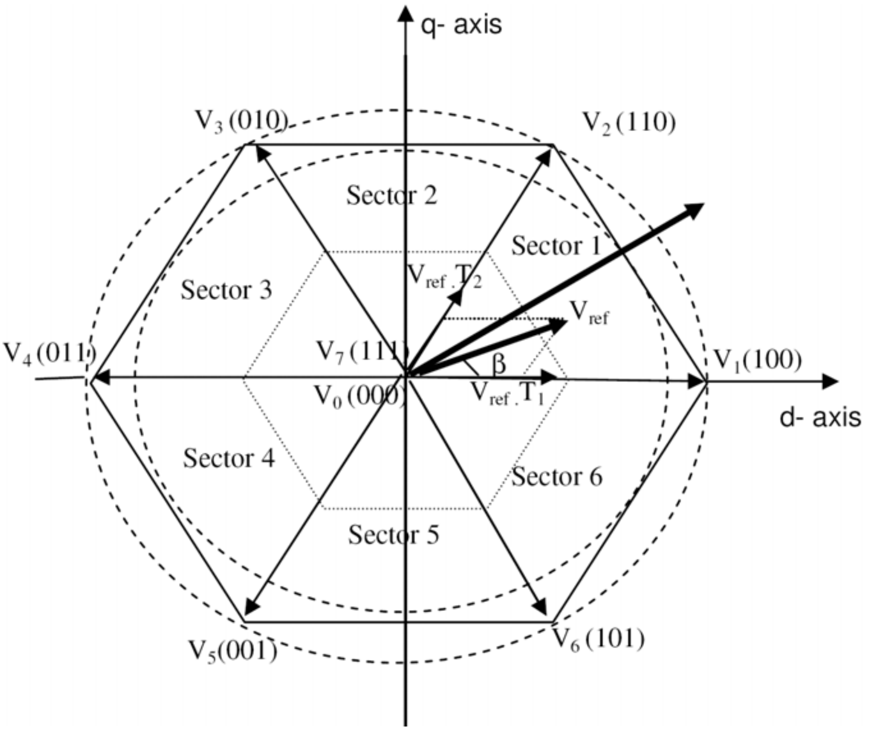

Figure-3. Voltage vector through modified SVPWM of ZSI.

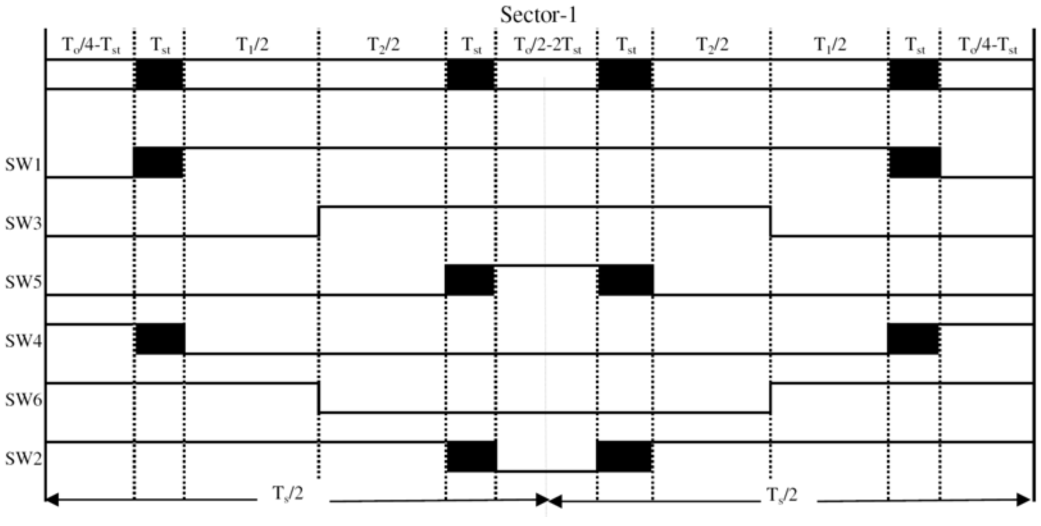

Figure-4. Switching pattern of modified space vector PWM in sector-1.

The variation of the voltage gain with the modulation index is analyzed for the conventional carrier based and the proposed SVPWM methods. The comparison is shown in Figure-5. From the proposed SVPWM highest value of voltage gain can be achieved at high modulation indices. But in other methods the same voltage gain is achieved at lower modulation indices that lead to high switching stresses.

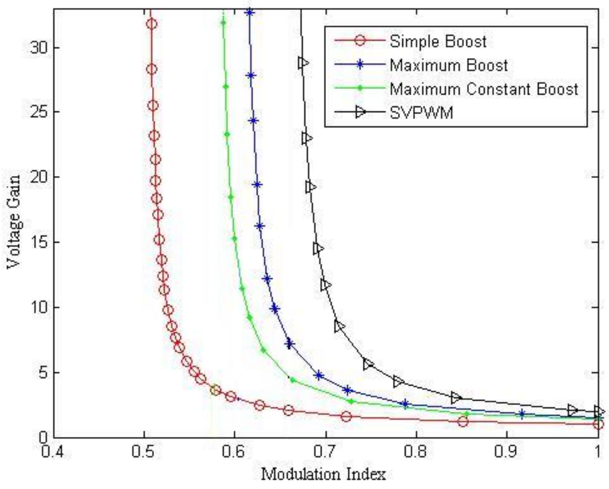

Figure-5. Voltage gain comparison for all PWM methods.

4. SIMULATION AND EXPERIMENTAL RESULTS

Simulation test beds using MatLab/Simulink were constructed to validate the effectiveness of the system models and control algorithms proposed. Parameters used for the simulation are shown in Table-1.

Table-1. Parameters used for simulation.

Parameter	Value
DC bus voltage	100 V
Z-source inductance (L1 and L2)	3mH
Z-source capacitance (C1 and C2)	1000μF
Load resistance	50Ω
Load inductance	10Mh
Switching frequency	10 kHz
Fundamental frequency	50 Hz

Simulation results for the proposed SVPWM are shown in Figure-6 to Figure-8. The output current is shown in Figure-6. Output phase voltage and line voltage waveforms are shown in Figure-7 and Figure-8.

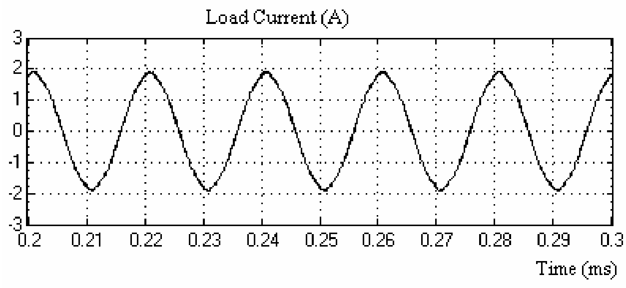

Figure-6. Load current waveform.

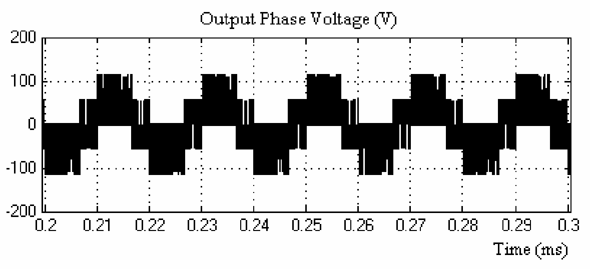

Figure-7. Output phase voltage waveform.

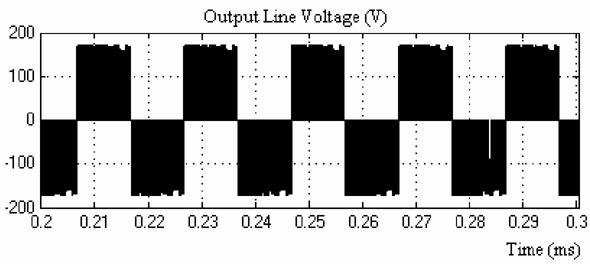

Figure-8. Output line voltage waveform.

Harmonic analysis on the output line voltage and output current was performed and the total harmonic distortion of load current was computed from simulation and was 1.74%. Total harmonic distortion of output phase voltage was computed from simulation and was 3.25%. Harmonic spectrums of load current and output phase voltage are shown in Figure-9 and Figure-10.

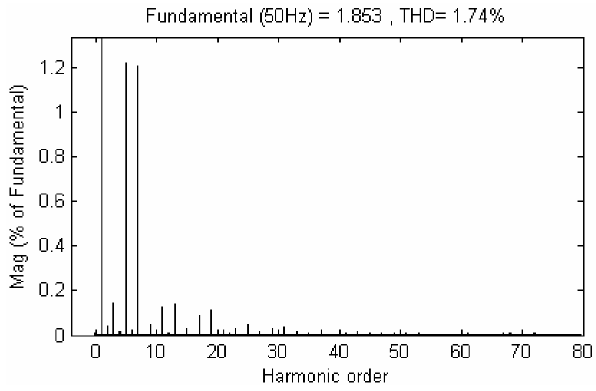

Figure-9. Harmonic spectrum of load current.

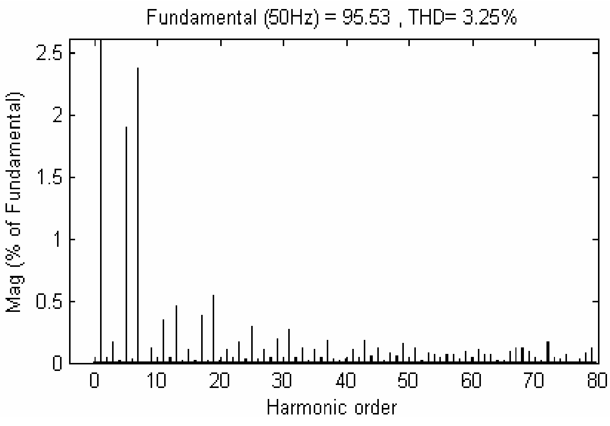

Figure-10. Harmonic spectrum of output phase voltage.

A laboratory model was constructed. The same parameters used in simulation were used. The proposed SVPWM algorithm was implemented by TMS320F2812 DSP processor. Figure-11 shows the output line voltage waveform, which strongly verifies the theoretical analysis and proposed SVPWM method.

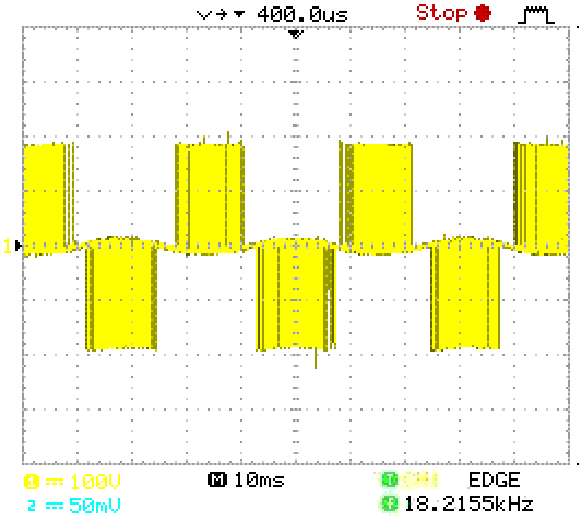

Figure-11. Experimental waveform of output line voltage.

5. CONCLUSIONS

A novel modified space vector PWM control method was carried out in this paper for three phase Z-source inverter. In this modified SVPWM method four shoot-through states were inserted in each sector for controlling the output voltage of Z-source inverter. The output AC voltage obtained from ZSI is no longer limited and can be boosted beyond the limit imposed by conventional VSI. Using MatLab/Simulink software package the simulation was performed to validate the proposed algorithm. The frequency spectra and the total harmonic distortion of the load current and voltages were obtained. Also the presented concepts were verified experimentally using a laboratory prototype.

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