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An Optimizing Methodology of ZSI with Suitable PWM Control Techniques

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Abstract: ***This paper presents a novel 3-phase Z-source inverter with six switches. The proposed system have different PWM techniques i.e., simple boost, maximum boost, maximum constant boost, modified space vector PWM etc., are reviewed and compared for Z-source inverter or traditional Z-source inverter. The comparison shows that the maximum constant boost control is the most suitable PWM control method for any ZSI topology. A model of Z-source inverter is built in MATLAB/SIMULINK and its performance is analyzed with different PWM control techniques. This project presents the performance characteristics of ZSI with reduced THD and high fundamental component. Simulation results prove the desired features and feasibility of the proposed system.***

Keywords: Z-source inverter, Pulse-width modulation techniques, Boost control, voltage stress, Vdc link voltage

1. Introduction

In traditional voltage–source inverters the two switches of the same phase leg can never be gated on at the same time doing so would cause a short circuit (shoot-through) to occur, which will destroy the inverter and the maximum output voltage obtainable can never exceed the dc bus voltage. These limitations can be overcome by Z-source inverter, which is explained in [1]. It consists of a unique impedance network coupled with the inverter main circuit to the power source. A two-port network that consists of a split inductor L_1 and L_2 and capacitors C_1 and C_2 are connected in X-shape is in use to provide an impedance source coupling the converter (or inverter) to the dc supply, load, or another convertor.

The Z-source inverter advantageously utilizes the shoot through states to boost the dc bus voltage by gating on both the upper and lower switches of same phase leg. Therefore, the Z-source inverter can buck and boost voltage to a desired output voltage that is greater than the available dc bus voltage. The reliability of the inverter is greatly improved because the shoot through caused by EMI noise can no longer demolish the circuit. Thus, it provides a low-cost, reliable, and highly efficient single–stage arrangement for buck and boost power conversion.

A traditional PWM 3-phase VSI operates in eight states i.e., six active and two null states. In active states, power is transported from the DC link to the AC output, whereas in null states the dc link capacitor is charged from the dc source [2]. The shoot through state is introduced within the null state of Z-source inverter.

This cannot be applied in VSI. The shoot through state in Z-source inverter enhances the voltage at the load end. The shoot-through states are inserted in such a way that, equal null intervals are maintained again at the start and end of the switching cycle, to accomplish the same optimal harmonic performance. Fig1.Shows the typical topology of three-phase ZSI

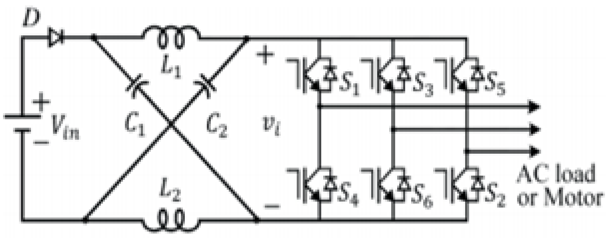

Figure 1: Typical topology of three-phase ZSI

This paper presents the comparison of line to line voltage, DC link voltage, voltage stress and % THD by using different boosting techniques for the Z-source inverter. The boosting techniques for the Z-source inverter used in this paper are the simple boost control, maximum boost, maximum constant boost and modified space vector PWM.

2. Circuit Assessment

Z-source inverter has a wide range of obtainable voltage which can be of any value between zero & infinity regardless of the input DC voltage.so,the Z-source is a buck-boost inverter.It is analyzed using voltage source inverter.The main feature of Z-source inverter is implemented by providing gate pulses including shoot- through pulses.However,the insertion of shoot-through states for different control methods become a key point for Z-source inverter.
In the shoot-through mode the Z-source network is shorted and in the active state,the Z-source network sees the load.This behavior can be simplified using the circuit given in the fig2.

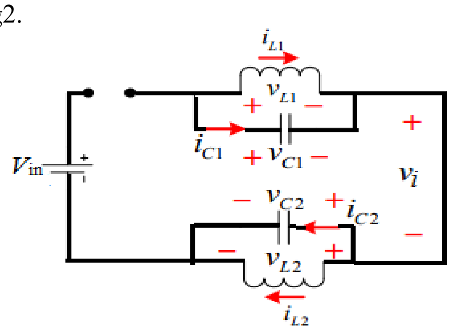

Figure 2(a): Shoot-through state of Z-source inverter

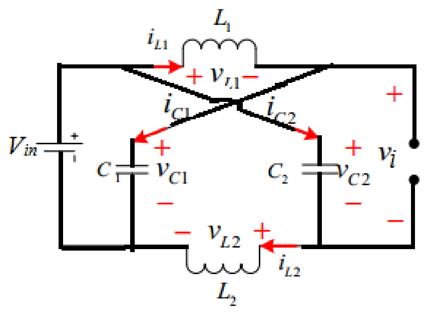

Figure 2(b): Active state of Z-source inverter

For simplication purposes, Z-source network parameters are selected as:

$$L_1=L_2 \ \& \ C_1=C_2$$

Which makes the Z-source network symmetrical.

Accordingly,the capacitor and inductor voltages of the Z-source network become

$$V_{C1}=V_{C2}=V_C \text{ and } V_{L1}=V_{L2}=V_L \qquad \text{------> (1)}$$

Fig2(a).Shows the shoot-through state.The diode D_1 is off because of withstanding reverse voltage.Assuming that the time of shoot through state is T_{sh} during a switching cycle T,From equivalent circuit in fig2. We have,

$$V_L=V_C, V_i=0 \qquad \text{------> (2)}$$

Similarly if the Z-source inverter is in the active for an interval of T_1 during the switching cycle T, From equivalent circuit in fig2(b).We have,

$$V_L=V_{in}-V_C ,$$

$$V_i=V_C-V_L=2V_C-V_{in} \qquad \text{------> (3)}$$

The average voltage of the inductors over one switching peroid (T) should be zero in steady state, From (2) &(3) we have

$$V_L = \frac{T_{sh}V_C+T_1(V_{in}-V_C)}{T} = 0 \qquad \text{------> (4)}$$

(or)

$$\frac{V_C}{V_{in}} = \frac{T_1}{T_1 - T_{sh}} = \frac{1-D}{1-2D} \qquad \text{------> (5)}$$

where, $D=\frac{T_{sh}}{T}$,$T=T_{sh}+T_1$

Correspondingly, the average dc link voltage across the inverter bridge can be

$$V_i = \frac{T_{sh}.0+T_1(2V_C-V_{in})}{T}$$

$$= \frac{T}{T_1 - T_{sh}} V_{in} = V_C \qquad \text{------> (6)}$$

$$V_i = B.V_{in} \qquad \text{------> (7)}$$

Where, $B = \frac{T}{T_1-T_{sh}} = \frac{1}{1-2\frac{T_{sh}}{T}} \geq 1$ ------> (8) ------>(8)

is the boost factor ensuing from the shoot-through zero state.

The output peak phase voltage from the inverter can be expressed as

$$V_{ac} = M.\frac{V_i}{2} \qquad \text{------> (9)}$$

Where M is the modulation index.

Using (7),(9) can be further expressed as $V_{ac} = M.B.\frac{V_0}{2}$ ------> (10)

The voltage stress is proportional to (B-G)

The boost factor B as expressed in (8) can be controlled by duty cycle of the shoot-through zero state over the non shoot-through states of the inverter PWM.

Note that the shoot through states are used to boost the magnetic energy stored in the DC side inductors L_1 and L_2 without short-circuiting the DC capacitors C_1 and C_2.This increase in inductive energy in turn provides the boost of voltage seen on the inverter output during the tradtional operating states of the inverter.

3. PWM Strategies

3.1 Simple Boost

A simple boosting method was used to control the shoot-through duty ratio. Fig3. Illustrates the simple boosting method that employs a straight line (V_P) equal to or greater than the peak value of the three phase references to introduce the shoot through duty ratio in a traditional sinusoidal PWM. If the triangular carrier signal is greater than V_P or smaller than V_N, the Z-source inverter is in shoot-through state. In order to produce an output voltage that requires a high voltage gain, a lower modulation index has got to be used. However, lower modulation indices result in greater voltage stress on the devices.

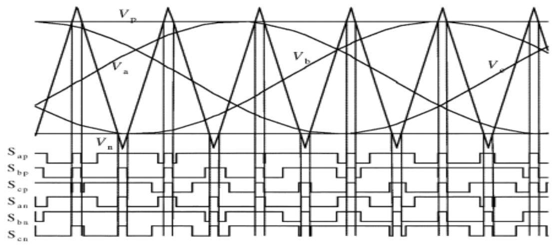

Figure 3: Pulse pattern for simple boost

3.2 Maximum Boost

The maximum boost strategy is an alternative to the simple boost method [3]. Commonly third harmonic injection method is used to increase the modulation index range. This can also be used here to increase the range of M so as to increase system voltage gain range. This method maintains the six active states unchanged and turns all zero states in to shoot-through states. Figure 4 shows the maximum boosting method.

The circuit is in shoot-through state when the triangular carrier wave is either greater than the maximum curve of the references (V_a,V_b&V_c) or smaller than the minimum of the references. The voltage stress in this method is much lower, i.e., the inverter can be operated to obtain a higher voltage gain. This method has a drawback of low-frequency ripples on the Z-source network.

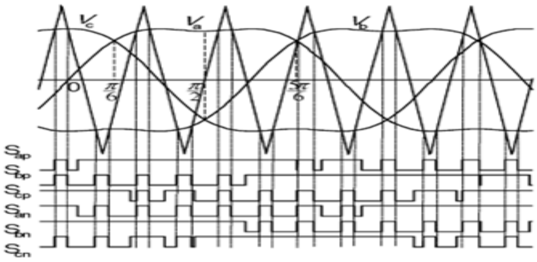

Figure 4: Pulse pattern for maximum boost

3.3 Maximum Constant Boost

Constant boost method achieves the maximum voltage gain while always keeping the shoot-through duty ratio constant [4]. This method requires the minimum inductance & capacitance because the inductor current and the capacitor voltage contain no low-frequency ripples associated with the output voltage, thus reducing the cost, volume and weight of the Z-source network. Fig5.shows the maximum constant boosting method.

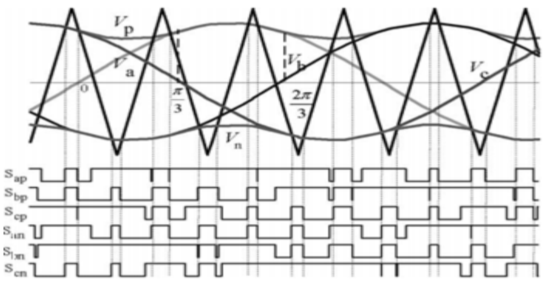

Figure 5: pulse pattern for Maximum constant boost

3.4 Modified SVPWM

Space Vector PWM aims at, for a sinusoidal excitation, the voltage space vector will rotate with uniform velocity and the tip of the vector will trace a circle.

SVM technique has widely used at industrial applications of power inverter because of lower current harmonics, higher modulation index, fast transient response and simple digital implementation. The objective of SVPWM technique is to approximate the reference voltage vector V_{ref} using eight space vectors. In SVPWM eight space vectors V_0~$V_7$are used, where V_1~V_6 are active vectors, V_0 and V_7 are zero vectors [5]. The basic space vector PWM is shown below. The reference voltage vector is divided in to the two adjacent voltage vectors V_1 and V_2, if the reference voltage vector is located at sector 1.

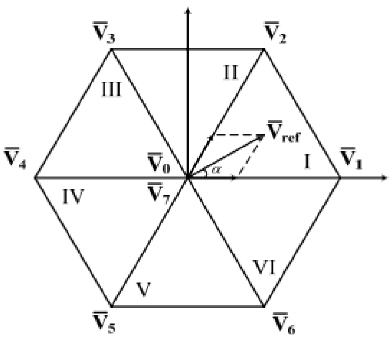

Figure 5: Basic space vector PWM

V_1 and V_2 are applied at the time T_1 and T_2, respectively, in one sampling interval, and T_0 is applied at time $T_0=T_s-(T1 + T_2)$.

This method is suitable to control the ZSI. Unlike the traditional SVM, the modified has an additional shoot through T_{sh} for boosting the dc link voltage of ZSI beside time intervals T_1, T_2 and T_Z. The structure of a typical three phase ZSI is shown in fig1. The relationship between switching variables $[a\ b\ c]^T$ and the line-to-line voltages is given by

Where, V_{dc} is the bus voltage

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \text{------> (11)}$$

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \text{------> (12)}$$

If the switching variables a, b, c, a', b' or c' is 1, the corresponding transistor is switched on; alternatively, the value 0 indicates switching off.

The dq transformation given in (13) can transform a 3 dimensional voltage vector
$V_{abc}= [V_a\ V_b\ V_c]^T$
in to a two dimensional vector in the dq coordinate frame $V_{dq}=[Vd\ Vq]^T$, which is written in (14).

$$T_{abc\text{-}dq} = \begin{bmatrix} 2/\sqrt{6} & -1/\sqrt{6} & -1/\sqrt{6} \\ 0 & 1/\sqrt{2} & -1/\sqrt{2} \end{bmatrix} \text{------>(13)}$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = T_{abc\text{-}dq} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix}$$

$$= V_{dc} \begin{bmatrix} \sqrt{6}/3 & -1/\sqrt{6} & -1/\sqrt{6} \\ 0 & 1/\sqrt{2} & -1/\sqrt{2} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \text{------>(14)}$$

The derived output phase voltages and corresponding voltage vectors are mapped in to the dq plane in fig7.

The reference voltage vector Vref of three phase ZSI [5] is obtained by mapping the desired three phase voltages to the dq plane through the following equation:

$$Vref= \begin{bmatrix} V_d \\ V_q \end{bmatrix} = T_{abc\text{-}dq} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{\sqrt{6}}{2}\, Vph \begin{bmatrix} \cos(\omega t) \\ \sin(\omega t) \end{bmatrix}$$

The selection of active vectors depends on the phase angle θ=ωt, it can be easily implemented once the phase angle is detected. However, the selection of zero vectors i.e., null vectors or shoot-through zero states is much more complex as the output voltage of all the zero vectors are the same.

In this approach, the maximum constant boost control method based on the space vector pulse- width modulation technique for a three phase ZSI is implemented, which is given in [6]. As mentioned above, in constant boost control, the shoot- through duty ratio is kept constant to achieve maximum voltage gain.

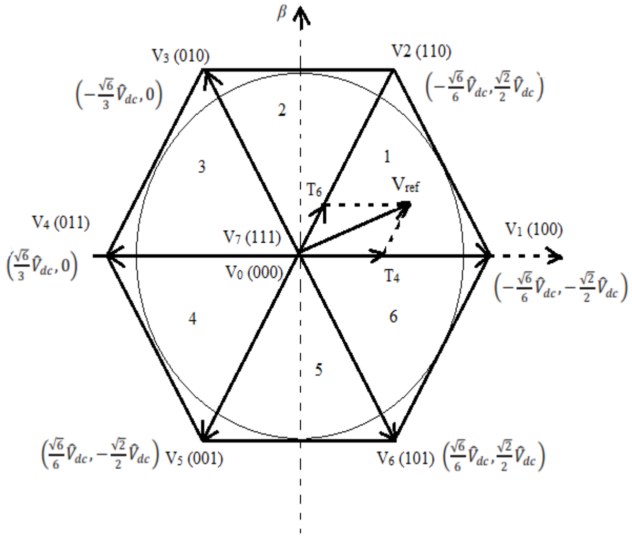

Figure 7: Basic space vectors and sectors of thee-phase ZSI

From table (1) it is known that the total time duration of zero states can be fixed to a certain value. Hence time duration of null states will be made to be zero, by which the maximum Tsh can be obtained.

The detailed expressions of T_{shmax} are expressed as

$T_s[1-\frac{\sqrt{3}}{2}M\cos(\theta-\frac{\pi}{6})]$ $0 \le \theta \le \pi/3$ $T_s[1-\frac{\sqrt{3}}{2}M\sin\theta]$ $\pi/3 \le \theta \le 2\pi/3$

$T_{shmax}=$ $T_s[1+\frac{\sqrt{3}}{2}M\cos(\theta+\frac{\pi}{6})]$ $2\pi/3 \le \theta \le \pi$ $T_s[1+\frac{\sqrt{3}}{2}M\cos(\theta-\frac{\pi}{6})]$ $\pi \le \theta \le 4\pi/3$ $T_s\left[1-\frac{\sqrt{3}}{2}M\sin\theta\right]$ $4\pi/3 \le \theta \le 5\pi/3$

$T_s[1+\frac{\sqrt{3}}{2}M\cos(\theta+\frac{\pi}{6})]$ $5\pi/3 \le \theta \le 2\pi$

From the above expression, T_{shmax} varies with θ.The sketch map of T_{shmax} versus θ is shown in fig8. Which indicates that T_{shmax} reaches its minimum value when θ= (2n+1π/6) (n=0, 1, 2….6).

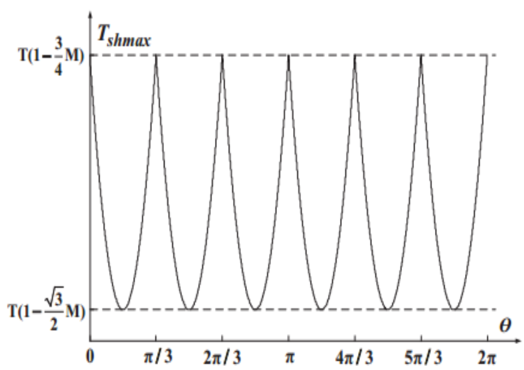

Figure 8: Sketch map of maximum shoot-through state time-duration

The minimum value of T_{shmax} (i.e., $T_s[1-\frac{\sqrt{3}}{2}M]$) satisfies the requirement of the maximum constant boost control method.

Thus the corresponding D_{sh}, B and G have exactly the same expressions of constant boost. Table (II) summarizes the expressions for different PWM control techniques.

4. Comparison of Voltage Stress Among Different Control Methods

Maximum constant boost method has a much lower voltage stress across the devices than the simple control, while having a slightly higher voltage stress than the maximum control method. At high voltage gain, the MSVPWM has the highest voltage stress.

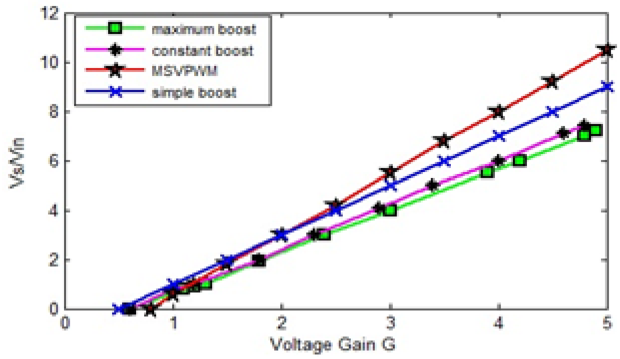

Figure 9: Voltage stress versus voltage gain for different PWM control methods

5. Results and Discussions

Simulation studies were conducted with the configuration shown in fig1.With the following parameters:

Z-source network: $L_1=L_2=1mH$
$C_1=C_2=1.3mF$

Switching frequency =10 kHz to verify the validity of the control strategies for 4 different PWM methods. The simulation results with the modulation index M=0.812 for simple boost, constant boost and modified SVM methods are shown in figs.10, 11 & 13 and M=1.107 for maximum boost control was shown in fig 12, where the input voltage is 150V. Fig14. Shows the motor speed, torque and stator current motor fed ZSI for maximum constant boost PWM method. Based on the above analysis, the practical values of Vdclink, voltage stress, output line to line RMS voltage and Voltage THD for RL-load are listed in Table III.

The aim of comprehensive simulation was a detailed comparison of ZSI features under various PWM control methods. The comparison shows that the constant boost control method is the most suitable PWM control method for a ZSI topology [9].

Table 1: Determination of time duration for each vector

Sector I ($0 \le \theta \le \pi/3$)	Sector II ($\pi/3 \le \theta \le 2\pi/3$)	Sector III ($2\pi/3 \le \theta \le \pi$)
$T_1 = \frac{\sqrt{3}}{2} T_s . M . \sin(\frac{\pi}{3} - \theta)$ $T_2 = \frac{\sqrt{3}}{2} T_s . M . \sin\theta$ $T_0 + T_{sh} = T_s - T_1 - T_2$ $= T_s[1 - \frac{\sqrt{3}}{2} M \cos(\theta - \frac{\pi}{6})]$	$T_2 = \frac{\sqrt{3}}{2} T_s . M . \sin(\frac{2\pi}{3} - \theta)$ $T_3 = \frac{\sqrt{3}}{2} T_s . M . \sin(\theta - \frac{\pi}{3})$ $T_0 + T_{sh} = T_s - T_2 - T_3$ $= T_s[1 - \frac{\sqrt{3}}{2} M \sin\theta]$	$T_3 = \frac{\sqrt{3}}{2} T_s . M . \sin(\frac{2\pi}{3} - \theta)$ $T_4 = \frac{\sqrt{3}}{2} T_s . M . \sin(\theta - \frac{\pi}{3})$ $T_0 + T_{sh} = T_s - T_3 - T_4$ $= T_s[1 - \frac{\sqrt{3}}{2} M \cos(\theta + \frac{\pi}{6})]$
Sector IV ($\pi \le \theta \le 4\pi/3$)	**Sector V ($4\pi/3 \le \theta \le 5\pi/3$)**	**Sector VI ($5\pi/3 \le \theta \le 2\pi$)**
$T_4 = \frac{\sqrt{3}}{2} T_s . M . \sin(\frac{4\pi}{3} - \theta)$ $T_5 = \frac{\sqrt{3}}{2} T_s . M . \sin(\theta - \pi)$ $T_0 + T_{sh} = T_s - T_4 - T_5$ $= T_s[1 + \frac{\sqrt{3}}{2} M \cos(\theta - \frac{\pi}{6})]$	$T_5 = \frac{\sqrt{3}}{2} T_s . M . \sin(\frac{5\pi}{3} - \theta)$ $T_6 = \frac{\sqrt{3}}{2} T_s . M . \sin(\theta - \frac{4\pi}{3})$ $T_0 + T_{sh} = T_s - T_5 - T_6$ $= T_s[1 + \frac{\sqrt{3}}{2} M \sin\theta]$	$T_6 = \frac{\sqrt{3}}{2} T_s . M . \sin(2\pi - \theta)$ $T_1 = \frac{\sqrt{3}}{2} T_s . M . \sin(\theta - \frac{5\pi}{3})$ $T_0 + T_{sh} = T_s - T_6 - T_1$ $= T_s[1 + \frac{\sqrt{3}}{2} M \cos(\theta + \frac{\pi}{6})]$

Table 2: Summary of different PWM control Methods expressions

Control method	Simple Boost	Maximum boost	Maximum constant boost	MSVPWM
D_0	1-M	$\frac{2\pi - 3\sqrt{3}M}{2\pi}$	$\frac{2 - \sqrt{3}M}{2}$	$\frac{2 - \sqrt{3}M}{2}$
B	$\frac{1}{2M - 1}$	$\frac{\pi}{3\sqrt{3}M - \pi}$	$\frac{1}{\sqrt{3}M - 1}$	$\frac{1}{\sqrt{3}M - 1}$
G	$\frac{M}{2M - 1}$	$\frac{\pi M}{3\sqrt{3}M - \pi}$	$\frac{M}{\sqrt{3}M - 1}$	$\frac{M}{\sqrt{3}M - 1}$
V_S	$(2G-1)V_{in}$	$\frac{3\sqrt{3}G - \pi}{\pi} V_{in}$	$(\sqrt{3}G-1)V_{in}$	$(\sqrt{3}G-1)V_{in}$

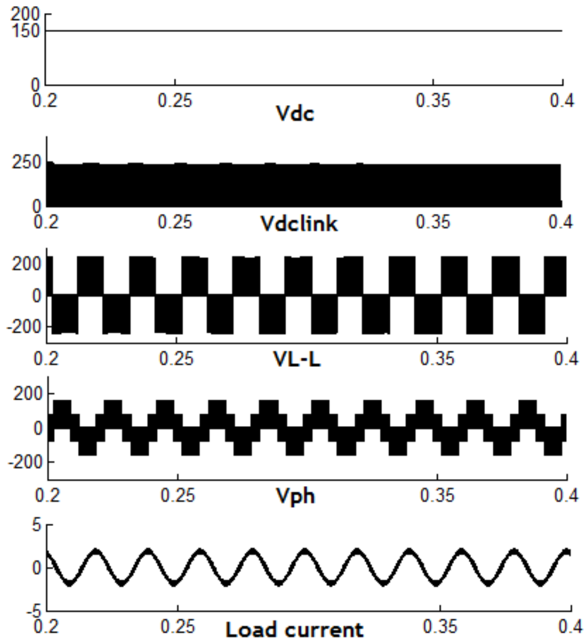

Figure 10: Simulation results for simple boost

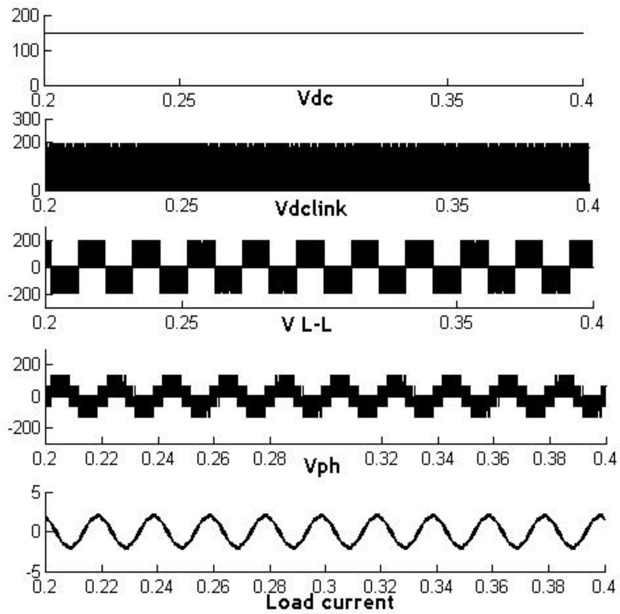

Figure 11: Simulation results for Maximum boost

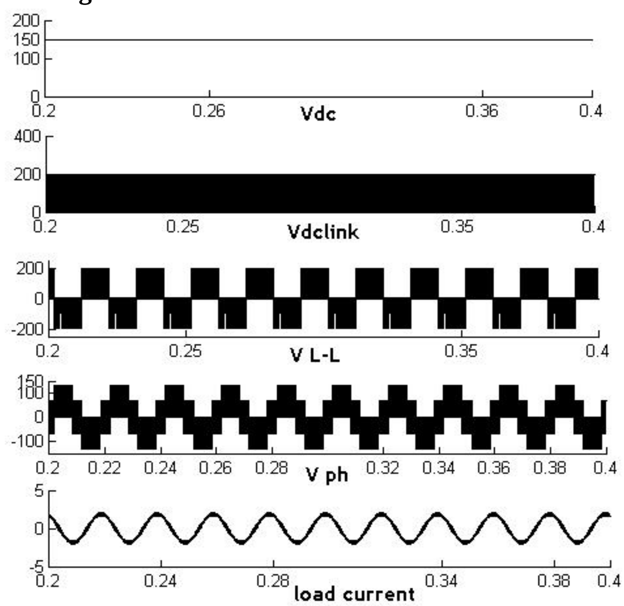

Figure 12: Simulation results for Constant boost

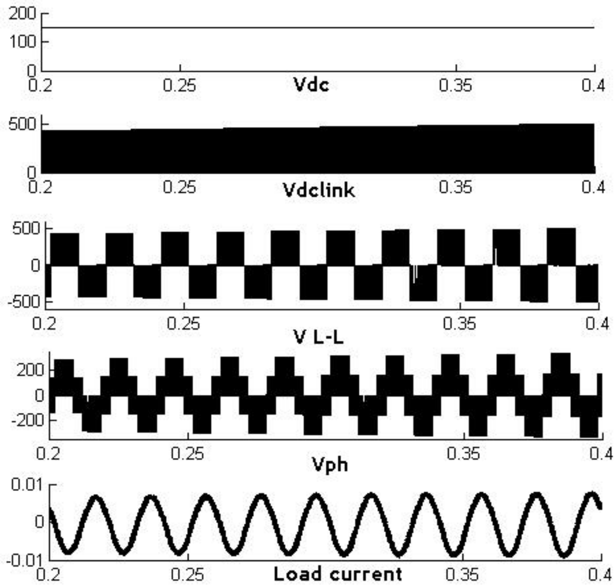

Figure 13: Simulation results for Modified SVPWM

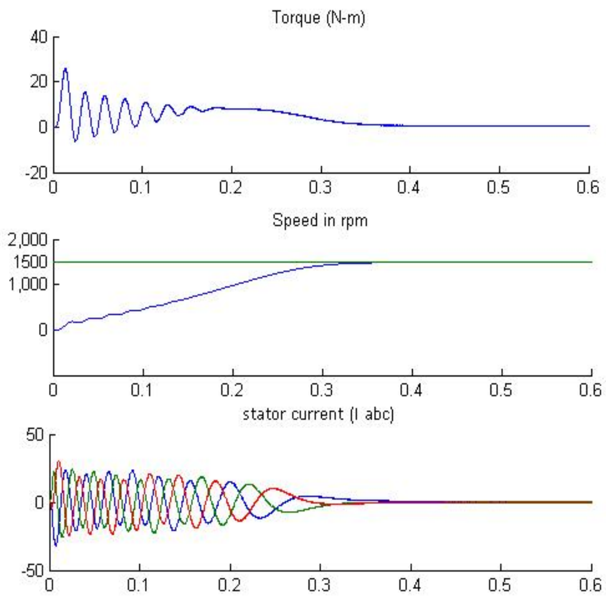

Figure 14: Motor speed, torque and stator current motor fed ZSI for Maximum constant boost PWM

Table 3: Simulation results summary for ZSI topology for different PWM control methods

	Simple Boost	Maximum Boost	Maximum constant Boost	MSVPWM
Vdclink	219.2	189.5	200.3	308.5
Vs	159.2	138.7	147	253.9
V_{LL}	162.6	161	165	231
THD_{VLL}%	88.12	57.98	67.73	78.86

6. Conclusion

This paper presents four PWM control methods for ZSI topology under the same input voltage, switching frequency and output load. The simulations have been developed in MATLAB/SIMULINK for four PWM techniques. A novel switching pattern in SVPWM is suggested i.e., the constant boost control method based SVPWM technique is implemented in this paper. The output AC voltage obtained from ZSI can be boosted beyond the limit imposed by conventional VSI.

The purpose of the system is to evaluate the performance of Z-source inverter for 4 different control methods. From the suitable control method, the Z-Source inverter is fed to IM drive system which is simulated by using MATLAB/SIMULINK software. The proposed methods are verified by MATLAB/SIMULINK simulation results for different PWM control methods.

7. Future Scope

Z-Source inverter is one of the most promising topology for Hybrid Electric vehicle applications. From the comparison of PWM strategies Z-Source inverter fed IM drive is applied for maximum constant boost control method. The Electro-magnetic Torque $T_e = T_L + J\frac{d\omega_m}{dt} + B\omega_m$

Where J=moment of Inertia which is related to weight of the vehicle.

If inertia increases, the torque (T_e) required running the vehicle also increases, which leads to improve the requirement of input power. Due to this, the efficiency reduces and cost increases.so, the size of the vehicle is to be reduced as far as possible. However, the inverter size and battery affects the performance of vehicles.

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