Comparison Analysis using Different Inverter Topologies for Traction System

V Sandhyarani
M-tech Student Scholar
Department of Electrical & Electronics Engineering,
ANURAG group of institutions (Formerly CVSR College of Engineering and technology) Engineering College,
Ghatkesar; Rangareddy (Dt); Telangana, India.

B Nageswara Rao
Assistant Professor
Department of Electrical & Electronics Engineering,
ANURAG group of institutions (Formerly CVSR College of Engineering and technology) Engineering College,
Ghatkesar; Rangareddy (Dt); Telangana, India.

Abstract—
The induction motor three phase drive provides an increase in the overall performance of electric traction equipment. With the ability to increase the level of the installed power, the train operator has been able to improve train operating times, the speed of the traction unit and the demand on the power supply system. With the introduction of inverter drives it has become necessary to complete a systems approach to ensure the safe operation of existing railway electrification infrastructure, and the safety critical areas of train signaling, and telecommunications. The conventional type of inverter suffers with the shoot through issues to avoid these problems traction drive systems using the Z-source inverter. By controlling the shoot-through duty cycle and modulation index, we can control the drive effectively. With the impedance network, the Z-source inverter can advantageously use the shoot through state to boost voltage. This one-stage power conversion and control system has higher reliability, higher efficiency, and lower cost. These facts make the Z-source inverter desirable for use in hybrid electric vehicles, as the cost and complexity is reduced when compared to the traditional inverters.

Keywords—Z source inverter; locomotives; constant boost control; electric traction

I. INTRODUCTION

Three phase locomotives which are in service today uses AC-DC-AC conversion technology for its speed control. The front end converter is H bridge type to reduce the harmonics injected into the source. Voltage source inverter fed squirrel cage induction motors are being used to drive the locomotive. A novel inverter, Z source inverter has been designed and developed which works in buck or boost configuration. The control strategy used for power conversion is simple boost control [1]. Maximum boost control strategy is used to generate switching signals which can increase the modulation index above unity [2]. Modified control strategy to the maximum boost is given in [3] which gives greater voltage boost for any given modulation index, namely constant boost control. It also mentions about the third harmonic injection to the constant boost control. Space vector PWM technique has been proposed which improves the stability of inverter system and keeps minimum voltage stress with variable input voltage. Only output voltage needs to be sensed and provides linear control to it [4]. Reference [5] explains a strategy to control the capacitor voltage and also the ac output voltage of the impedance source inverter. It is given that by controlling the capacitor voltage linearly the transient response of dc capacitor voltage was improved. The output ac voltage was controlled by controlling the peak value. Pulse width modulation technique which minimizes the inductor current ripple has been proposed. The shoot through time intervals are rearranged according to active and zero state intervals with constant total shoot through time [6]. To reduce the line harmonics and improves the power factor, Z-source inverter system with diode rectifier at the front end for general-purpose motor drives has been proposed [7]. Z source inverter is applied for automotive applications such as hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), for fuel cell hybrid electric vehicles (FCHEV) and performance is analyzed in both motoring and regenerative modes of operations [8]. In this work, voltage source inverter is replaced with Z source inverter in locomotives and performance is analyzed in the constant torque region. Variable voltage variable frequency method of speed control is adopted for speed control of traction motors as in the existing locomotives. The control topology for
impedance source (Z source) inverter is constant boost control with third harmonic injection.

II. TYPES OF INVERTERS

There are three basic types of inverters commonly employed in adjustable AC drives system i) voltage source inverter ii) current source inverter iii) Z-source inverter. The variable voltage inverter (VVI), or square-wave six-step voltage source inverter (VSI), receives DC power from an adjustable voltage source and adjusts the frequency and voltage. The current source inverter (CSI) receives DC power from an adjustable current source and adjusts the frequency and current. Z-source inverter is the combination of voltage source inverter and current source inverter.

A. Voltage-Source Inverter

Fig.1 shows the three-phase voltage-source inverter structure. A DC voltage source supported by a relatively large capacitor feeds the 3-phase inverter circuit. The DC voltage source can be a battery, fuel-cell stack, diode rectifier, and/or capacitor. Six switches are used in the main circuit each is traditionally composed of a power transistor and an anti-parallel (or freewheeling) diode to provide bidirectional current flow and unidirectional voltage blocking capability. It has certain limitation of the voltage source inverter. The AC output voltage is limited below and cannot exceed the DC voltage. The V-source inverter is a buck (step-down) inverter for DC-to-AC power conversion. The upper and lower devices of each phase leg should not be gated on simultaneously because a shoot-through would occur and destroy the devices. The shoot-through problem by electromagnetic interference (EMI) noise’s misgating-off is a major killer to the converter’s reliability.

B. Current-Source Inverter

Fig.2 shows the three-phase current-source inverter structure. A DC current source feeds the 3-phase inverter circuit. The DC current source can be a relatively large DC inductor fed by a voltage source such as a battery, fuel-cell stack, diode rectifier, or thyristor converter. Six switches are used in the main circuit each is traditionally composed of a semiconductor switching device with reverse block capability such as a gate-turn-off thyristor (GTO) and SCR or a power transistor with a series diode to provide unidirectional current flow and bidirectional voltage blocking.

The current source inverter has certain Limitations of the AC output voltage has to be greater than the original DC voltage that feeds the DC inductor or the DC voltage produced is always smaller than the AC input voltage. The I-source inverter is a boost inverter for DC-to-AC power conversion. At least one of the upper devices and one of the lower devices have to be gated on and maintained on at any time. Otherwise, an open circuit of the DC inductor would occur and destroy the devices. The open-circuit problem by EMI noise’s misgating-off is a major concern of the inverters reliability. The main switches of the I-source inverter have to block reverse voltage that requires a series diode to be used in combination with high-speed and high performance transistors such as insulated gate bipolar transistors (IGBTs). This prevents the direct use of low-cost and high-performance IGBT modules and intelligent power modules (IPMs).

C. Z-Source Inverter

Z-source inverter is the combination of voltage source inverter and current source inverter as shown in Fig.3. A two-port network that consists of a split-inductor L1 and L2 and capacitors C1 and C2 connected in X shape is employed to provide an impedance source (Z-source) coupling the inverter to load, or another converter. Switches used in the inverter can be a combination of switching devices and diodes such as the anti-parallel combination as shown in Fig.1. The series combination as shown in Fig. 2. The Z-
source inverter intentionally utilizes the shoot through zero states to boost DC voltage and produce an output voltage greater than the original DC voltage. At the same time, the Z-source structure enhances the reliability of the inverter greatly because the shoot through states that might be caused by EMI noise can no longer destroy the inverter. For the traditional V-source inverter, the DC capacitor is the sole energy storage and filtering element to suppress voltage ripple and serve temporary storage. For the traditional I-source inverter, the DC inductor is the sole energy storage/filtering element to suppress current ripple and serve temporary storage.

III. INDUCTION MOTOR

The AC induction motor is considered since its discovery as actuator privileged in the applications of constant speed, and it has many advantages, such as low cost, high efficiency, good self starting, its simplicity of design, the absence of the collector brooms system, and a small inertia. The induction motor is a rotating electric machine designed to operate from a 3-phase source of alternating voltage. For variable speed drives, the source is normally an inverter that uses power switches to produce approximately sinusoidally-distributed voltages and currents of controllable magnitude and frequency. A cross section of a two-pole induction motor is shown in Figure 4.

Fig.4 cross-section of induction motor

Slots in the inner periphery of the stator accommodate 3-phase winding a, b, c. The turns in each winding are distributed so that a current in a stator winding produces an approximately sinusoidally-distributed flux density around the periphery of the air gap. When three currents that are sinusoidally varying in time, but displaced in phase by 120° from each other, flow through the three symmetrically-placed windings, a radially-directed air gap flux density is produced that is also sinusoidally distributed around the gap and rotates at an angular velocity equal to the angular frequency, of the stator currents. The most common type of induction motor has a squirrel cage rotor in which aluminium conductors or bars are cast into slots in the outer periphery of the rotor. These conductors or bars are shorted together at both ends of the rotor by cast aluminium end rings, which also can be shaped to act as fans. In larger induction motors, copper or copper alloy bars are used to fabricate the rotor cage winding. As the sinusoidally-distributed flux density wave produced by the stator magnetizing currents sweeps past the rotor conductors, it generates a voltage in them. The result is a sinusoidally-distributed set of currents in the short-circuited rotor bars. Because of the low resistance of these shorted bars, only a small relative angular velocity, \( r \), between the angular velocity, \( s \), of the flux wave and the mechanical angular velocity of the two-pole rotor is required to produce the necessary rotor current. The relative angular velocity, \( r \), is called the slip velocity. The interaction of the sinusoidally-distributed air gap flux density and induced rotor currents produces a torque on the rotor. The typical induction motor speed torque characteristic is shown in Figure 5.
Fig. 5 Induction Motor Speed-Torque Characteristics

IV. DIODE-CLAMPED MULTILEVEL INVERTER (DCMI)

To explain how the staircase voltage is synthesized, point O is considered as the output phase voltage reference point. Using the five-level inverter shown in Fig. 4.13, there are five switch combinations to generate five level voltages across A and O. Table 4.1 shows the phase voltage level and their corresponding switch states.

The diode-clamped inverter was also called the neutral-point clamped (NPC) inverter when it was first used in a three-level inverter in which the mid-voltage level was defined as the neutral point. The diode-clamped multilevel inverter uses capacitors in series to divide up the dc bus voltage into a set of voltage levels. To produce m levels of the phase voltage, an m level diode-clamp inverter needs m-1 capacitors on the dc bus. A single-phase five-level diode-clamped inverter is shown in Fig. 4.13. The dc bus consists of four capacitors, i.e., C1, C2, C3, and C4. For a dc bus voltage Vdc, the voltage across each capacitor is Vdc/4, and each device voltage stress will be limited to one capacitor voltage level, Vdc/4, through clamping diodes. DCMI output voltage synthesis is relatively straightforward.

<table>
<thead>
<tr>
<th>Output V_{AO}</th>
<th>V_5=V_{dc}</th>
<th>V_4=3V_{dc}/4</th>
<th>V_3=V_{dc}/2</th>
<th>V_2=V_{dc}/4</th>
<th>V_1=0</th>
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<tbody>
<tr>
<td>Switch states</td>
<td>S_{a1}</td>
<td>S_{a2}</td>
<td>S_{a3}</td>
<td>S_{a4}</td>
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Table: 1 Diode-clamped five-level inverter voltage levels and their switch states

V.SYTEM DESCRIPTION

Electric locomotive is getting the power supply from the traction substations through the pantograph mounted on top of it. The ac supply is step down using a transformer inside the locomotive. The traction
transformer has four secondary windings, each of which is connected to AC-DC converter. Two converters are connected in H bridge topology and the outputs of the converters are fed to the z source inverters through the dc link. There are six motors grouped in two, each contains three parallel connected traction motors. The schematic and power circuit diagram of ZSI fed locomotive drive is given in fig.1-2

![Figure 1 Schematic diagram of locomotive fed by impedance source inverter](image)

**Figure 1 Schematic diagram of locomotive fed by impedance source inverter**

![Figure 2 Power circuit of one group of ZSI fed traction motor drive](image)

**Figure 2 Power circuit of one group of ZSI fed traction motor drive**

The stator reference frame model differential equations of induction motor in matrix form [9] is given by equation (1)

\[
\begin{bmatrix}
V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr}
\end{bmatrix} =
\begin{bmatrix}
R_s + L_m \omega_r & L_m & 0 & 0 \\
0 & R_r + L_p & 0 & L_m \\
-\omega_r L_m & -\omega_r L_m & R_r + L_p & -\omega_r L_r \\
0 & \omega_r L_m & R_r + L_p & \omega_r L_r
\end{bmatrix}
\begin{bmatrix}
i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr}
\end{bmatrix}
\]

(1)

The electromagnetic torque is given by equation (2) where P represents the number of poles.

\[
T_e = \frac{3}{2} L_m (i_{qs} i_{dr} - i_{ds} i_{qr})
\]

(2)

Where Rs and Rr are the stator and rotor resistances, Ls, Lr and Lm represent the stator, rotor and magnetizing inductances indicated the differential operator d/dt, \( \omega_r \) is the speed of rotor in rad/s. Vqs, Vds, Vqr, Vdr represents the quadrature and direct axes voltages of stator and rotor respectively, iqs, ids, iqr and idr are the quadrature and direct axes currents of stator and rotor respectively. The control strategy for Z source inverter adopted is constant boost control with third harmonic injection [3].

**A. Control topology**

In this topology, 1/6th of the third harmonic is added with the fundamental signal to get the modulating wave. It is compared with the triangular carrier wave to get the switching signals for the non shoot through period. The pulses for shoot through period are obtained by comparing two straight lines with triangular carrier signal. When the straight line is less than or greater than the carrier wave, shoot through pulses are generated.

The voltage gain is given by

\[
G = MB = \frac{V_{ac}}{V_{dc}/2} = \frac{M}{\sqrt{3}M-1}
\]

(3)

The boost factor, B is given by

\[
B = \frac{1}{1-\frac{T_a}{T}} = \frac{1}{\sqrt{3}M-1}
\]

(4)

The voltage stress, Vs is given by

\[
V_s = BV_{dc} = (\sqrt{3}G - 1)V_{dc}
\]

(5)

Where is the dc voltage at the input of ZSI, to be the shoot through period in a switching cycle T, Vs is the phase voltage at the inverter output. The speed control strategy used for traction motors is open loop variable voltage variable frequency. The flux is kept constant in
the constant torque mode. The schematic of pulse generation by open loop v/f law for constant boost controlled Z source inverter fed traction motor is given in fig.3 The value of modulation index for a particular frequency, \( f \) is determined from the equation (6)

\[
\overline{V_{ac}} = MB \frac{V_o}{2} = f \star \left( \frac{V}{f} \right) \sqrt{2/\sqrt{3}}
\]  

(6)

The single phase front end converter is capable of maintaining constant dc voltage and input power factor at unity. The schematic of the inner current loop and outer voltage loop is given in fig.4 and fig.5 respectively.

**B. Design of impedance network parameters**

The value of inductance and capacitance are calculated using the parameters of traction motors used in three phase locomotives [11].

\[
L_1 = L_2 = L = \frac{V_o T (2V_{ac} - V_o)}{2k_i I_o (4V_{ac} - V_o)}
\]  

\[
C_1 = C_2 = C = \frac{I_o T (2V_{ac} - V_o)}{2k_v V_o (4V_{ac} - V_o)}
\]  

(7)  

(8)

Where \( M \) is the modulation index and \( k_i , k_v \) represent current ripple and voltage ripple respectively.

**VI. SIMULATION RESULTS AND DISCUSSION**

The z source inverter fed locomotive drive is modelled and simulated in MATLAB/Simulink. The stator current, speed of the motor and torque for rated load are plotted.
Figure: 8 Simulink diagram 5 level Inverter Output Voltage without z source

Figure: 9 Simulink diagram of with z source inverter fed by locomotive drive

Figure: 10. Simulink diagram of proposed with z source inverter fed by locomotive drive

Figure: 11. Simulink diagram of proposed without z source inverter fed by locomotive drive

Figure: 12. Complete Simulink diagram of proposed with z source inverter fed by locomotive drive

Figure: 13. Proposed Performance Characteristics of Induction Motor At full load torque = 50 N·m and speed=1800 rpm With Multilevel inverter
Figure 14: Performance Characteristics of Induction Motor at full load torque = 50 N-m and speed=1800 rpm Without Multilevel inverter.

Figure 15: Proposed Performance Characteristics of Induction Motor at 3/4th load torque = 37 N-m and speed=1800 rpm With Multilevel inverter.

Figure 16: Performance Characteristics of Induction Motor at 3/4th load torque = 37 N-m and speed=1800 rpm Without Multilevel inverter.

Figure 17: Proposed Performance Characteristics of Induction Motor at half load torque = 25N-m and speed=1800 rpm With Multilevel inverter.

Figure 18: Performance Characteristics of Induction Motor at half load torque = 25 N-m and speed=1800 rpm Without Multilevel inverter.

Figure 19: Thd of Voltage with Z Source Inverter with Multilevel inverter.
IV. CONCLUSION
Z source inverter fed locomotive drive is modelled and simulated in MATLAB/Simulink environment. The topology used for generating switching signals is constant boost control with third harmonic injection. To analyze the performance of inverter voltage, speed and torque at different load conditions Shoot through problems overcome by using z source inverter It uses phase disposition SPWM control method, which is less complex control method since it uses only positive carriers, associated cost is reduced and gives less THD. Indian railways granting the permission for this project.
REFERENCES


