Analysis of Z-Source Inverter fed Asynchronous Motor for Electric Vehicle Applications

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Abstract. ELECTRIC VEHICLES are first introduced in 19th century but at the beginning, performance of electric vehicles is very poor in efficiency, speed, cost, controlling the vehicle. During this period IC engines plays major active role in transportation and even if the electric vehicles are having the above-mentioned drawbacks, but extensively used in electric locomotives and various applications. There is a gradual incising the cost of petroleum products again the research looking back into electric vehicles. But the fast development of power electronics and the battery management system and the reduced size of battery push forward towards the progress of electric vehicles. Due to the drastic improvement in power electronics region the controlling of electric vehicles are become easy and the charging time also reduced drastically. In conventional Voltage and current source inverters, a voltage stress across the power switches is a biggest concern to improve the system efficiency. To limit the drawbacks of classical converters, in this work an impedance source inverter fed asynchronous motor is proposed. In turn control the electric vehicle operation both in accelerating and decelerating periods. The proposed inverter controlled various pulse width modulation control strategies and corresponding Total harmonic distortion analyzed. The DC link Voltage regulation, stator and rotor currents, torque and speed of the proposed asynchronous motor drive performance for the designed EV setup have been investigated through MAT LAB simulation.

Keywords: Z-Source Inverter, Electric Vehicle (EV), Induction Motor, Sine PWM, Shoot through State(ST), Non Shoot through State(NST), Boost Control.

1. Introduction
The electric vehicle consists of various parts like motor, battery, converter and the entire mechanical system with supporting components. The choice of each and every part is a considerable challenge in electric vehicles since we are using power electronic devices even if the small variations in parameters the switches get damaged, appropriate components can be consider for smooth continuous operation. The selection of motor is one of the biggest tasks because there are different types of motors for propulsion of electric vehicles depends on operator expectations, vehicle restraint and power source, but each motor having their own features for controlling the EV parameters. In Electrical vehicle design, the selection of battery and motor is a extensive challenge, because the weight and placement of those things plays major role in stability and millage of vehicle. However, the millage range depends on battery rating and now the research on batteries are going very fast to reduce the size and weight, now the thing is selection of motor for electric vehicle for propulsion. The available motors are SRM (switched reluctance motors), PMSM (permanent magnet synchronous motors), BLDC (brush less DC motors), IM (induction motors), DC motors etc., in two wheelers, more often used motors are BLDC (brush less DC motors), DC motors (DC hub motors) but performance and controlling wise. Out of which the induction motor has a grater advantages [1] are there so in this model asynchronous motor is used for propulsion of electric vehicle that is electric bike. Asynchronous motor is nothing but induction motors are available for low cost, robust, ease to controlling for EV applications.IM (induction motor) has grater advantages over-all above-mentioned motors. With the using of induction motors in electric vehicles the following advantages are achieved.
- Good speed control is possible over a wide range

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Motor is robust
Converter design for controlling is simple
Low cost
Maintenance is less

Even the HEV’s have higher efficiency than both ICE and EV’s the hybrid electric vehicles has following requirements for their propulsion
1) It requires large power for starting
2) In starting the torque requirement is very high and in hill climbing’s also the torque requirement is high so corresponding power density also high.
3) In constant power region and constant torque region very wide range of speed requires.
4) It requires fast torque response.
5) Cost should be less
6) Regenerative braking with high efficiency is needed

2. Related Work

In earlier days, the efficiency of (ICE) internal combustion engines is too less due to the losses in different stages, hence after enormous research, the efficiency of electric vehicle is far better than the IC engine vehicles. Table 1 shows the different types of vehicles. The pollution is increased with the usage of IC engine vehicles and due to losses in several stages in IC engine vehicles the efficiency also reduces as discussed in Table 1. The selection of electric -driving force system in the vehicle rests on 3-factors i.e to satisfy drivers anticipation, vehicle control and energy source. In view of all the conditions as per the choice of driver entire motor functioning is not compactly designed. A careful selection of the opt electric driving force system required for a vehicle is considered as the most crucial core.

Table 1. Different Types of Vehicles

| Types of Vehicle  | Available at wheels per 1kwh(unit) |
|-------------------|------------------------------------|
| Electric vehicles | 0.282                              |
| Hybrid EV’s       | 0.192                              |
| Diesel Engine     | 0.272                              |
| Gasoline vehicles | 0.195                              |

Now the well to tank efficiency of internal combustion engine is increased by 0.5% in coming 10 years that is by year 2030. This improvement in efficiency is due to the refining process. Now a days the technology is improving in very fast rate, with the improving technology the efficiencies of various types of vehicles are improved in future that is by 2030 are as follows

- Diesel engine to 75%
- Gasoline engine to 50%

Even if the efficiency is increased the pollution factor also is increased and the efficiencies of different sources [2]-[3] are shown in Table 2.
| Type of Fuel                        | Efficiency (%) |
|-----------------------------------|----------------|
| Thermal power plant               | 54             |
| Gas Fired                         | 65             |
| Fossil Fuel Fired thermal Plant   | 44             |
| Hydro Plant                       | 14             |
| Nuclear Plant                     | 5              |
| Solar                             | 18*            |
| Wind Power                        | 12*            |
| Other Renewable Energy            | 20             |

From Table 2 the efficiencies of various energy sources are less but with the increase in power electronics converters and due to environmental conditions in present days the efficiency of solar and wind plants are increased to 28% and 22% respectively in coming few years. The energy available at well is utilized at a rate of 0.959. As research is increasing continuously on renewable energy, the per unit cost is reduced. However, the electric vehicle is best choice for consumers to save amount and save the environment. There various factors that are looking forward as advantageous to the EV users.[4]-[6]

- Requirement essential Gas is absent
- Money savings
- Eliminate Emissions
- Safe drive is possible
- Cheap in cost
- Maintenance cost is low.
- Very less Noise

The simplified single line diagram is shown in Fig.1 proposed ZSI inverter fed asynchronous motor with electrical driving shaft wheels. The power source is considered as 3-phase alternating supply, given supply is rectified as dc supply by using rectifier unit. Z-source network taken supply from the rectifier unit and output of the proposed network is given to the inverter. A detailed single line diagram is represented in Fig.2, inverter output is fed to the proposed motor for smooth operation of electric vehicles.

![Fig.1 ZSI fed Induction Motor Drive with EV](image)

![Fig 2.Single Line Diagram of the Proposed Drive EV Application](image)

**3. Proposed ZSI Converter**

The main important part in EV is Converter. The converter plays major role in electrical vehicle in speed controlling, battery management system, stepping up of given input and conversion of DC into AC. There are various types of converters are used to design the EV applications. In EV design two types of power conversions states necessary, to achieve these two states traditional voltage source converter shown in Fig.3, acting as buck and boost modes. VSI produces the high currents when it operates at shoot through mode and switches may get
damaged with higher voltage levels. If the converter is operated in boost mode with less input voltage, there are some power loss occurred in the system, hence overall system efficiency is reduced and weight of the system is increased these factors are undesired for electric vehicle. To avoid this from system the new technique in electric vehicles is introduced that is Z-source inverter [7,13]-[9]. Then traditional VSI is controlled by adding an impedance network in the system.

On introduction of ZSI between DC source and classical inveter shown in Fig.4 and it is operated in two states like Shoot through state (ST) and Non Shoot through state (NST). In ST state capacitor voltage is more than the input DC voltage, hence diode is reverse biased and inveter terminals are shorted. Due to diode reverse biased no power is transferred from source to load and shown in Fig 5(a). Where as in NST state diode is forward biased and the inverter acts as open circuited hence power is transferred from source to load and is shown in Fig 5(b).

![Fig.3 Classical VSI fed AC load](image)

![Fig.4 Introduction of ZSI in between DC source and Inverter](image)

![Fig.5 ZSI in (a) ST and (b) NST modes of operation Equivalent Circuit](image)
4. Control Schemes for ZSI

There are so many Pulse Width Modulation methods exist in the literature to control the classical voltage source converter. To improve the voltage, there are seven shoot through states are allowed for the proposed ZSI converter without disturbing the volt-sec balance normalized average voltage. With the current PWM, ZSI shoot through states are further used to bring out the various modulation approaches in turn to control the proposed ZSI fed AC load

4.1. Simple Boost Control

In classical pulse width modulation technique, all the voltages ‘V_0’, ‘V_0’, and ‘V_c’ are sinusoidal reference signals, compare by means of triangular carrier signals to control the inverter. If the reference signals are higher than the carrier signal, then upper arm switches are controlled and if reference signals are lower than triangular carrier signals lower arm switches are controlled. Here, taking care off about the triangular frequency which is higher than the reference signals. From the classical PWM technique, the required amount of AC voltage is sufficiently obtained by the source voltage. But practically, may not get the desired AC voltage from the DC source voltage, a new PWM technique is introduced to improve the voltage[10].

On introduction of ST states, a null voltage developed across the load, as a result no change in the PWM[15] operation. Shoot through states generate by switching ON the any leg switches and any phase, but the control signals S_{up} and S_{down} are at logic high. For each phase, shoot through period is divided equally. In this technique, switching losses occurs at a high rate due to voltage stress across the switches. Voltage gain decreases due to inadequacy of voltage rating. The complete cycle of switching period is represented as T_s, the shoot through period represented as T_{sh} and Zero state time and duty ratio for shoot through is D_{sh}. Boost factor B, Voltage gain G, Modulation index are derived from simple boost control (SBC) as follows in eq (1) and (2).

\[ B = \frac{1}{1 - 2D_{sh}} - \frac{1}{1 - \frac{D_{sh}}{T_s}} \]

Where Duty Ratio \( D_{sh} = \frac{T_{sh}}{T_s} \) (1)

\[ G = \frac{\frac{V_m}{\sqrt{2}}}{V_{dc}} \]

(2)

4.2. Maximum Boost Control and Maximum Boost Third Harmonic Injection PWM Control

Here, conventional zero states are appear as shoot through states. Moreover, switching devices voltage stress is diminished by complete utilization of null states. In line a cycle ST state through duty ratio is varied but –12ripples occurs in the inductor current. Hence, a high inductance required for low and variable frequency applications. The most important feature of the ZSI is diminishing the voltage across the switches. From the SBC method eq (3) to eq (5), for any voltage gain, lower the value of B and maximize the value of M. Also boost factor increase turn to improve the voltage gain by continue the ST state duty ratio as high as possible[11]-[12].

\[ B = \frac{1}{1 - 2D_{sh}} - \frac{1}{1 - \frac{D_{sh}}{T_s}} \]

\[ D_{sh} = \frac{2n - \sqrt{3} \pi}{2 \pi} \]

(3)

The maximum duty ratio

\[ m = \frac{\pi}{\sqrt{3} \pi - \pi} \]

(4)

Voltage stress calculated from the above equation as follows

\[ V_S = B^*V_{dc} = \frac{n}{\sqrt{3} \pi - \pi} V_{dc} \]

(5)

The boost factor is increased due to increase ST state duty ratio to obtain a precise modulation index without any change in the output waveform. Due to this precise modulation index, wider range of operation is possible for any voltage which also reduces the voltage across the switches. On the other hand, ripples occur in line frequency current, to overcome this drawback introduced another method called maximum constant boost control. In view of this technique, voltage stress is diminished across the switch along with there is no line frequency current ripples. Third harmonic injection is also similar, commonly the range of M.I is varied≤1, with this range a stress will be occur on the switches. To limit the stress and improve the voltage gain M.I is varied over modulation range in Third harmonic Injection control scheme.
4.3. Maximum Constant Boost Control

Voltage gain is enhanced by keeping the boost level constant achieved from maximum constant boost control. Without any distortions occurred in the line frequency current is an added advantage of this control and also it reduces the requirement of inductance and capacitance of the proposed ZSI network. Two modulation curves are added $V_p$ and $V_n$ along with regular reference signals $V_a, V_b, V_c$ to obtain a constant ST duty ratio. To get three time more output frequency, the two modulation curves are periodical. The carrier or triangular signal is varied above the upper modulation signal $V_p$ or below the lower modulation signal $V_n$ to get the ST zero state. Where as the intermediate stage constant like traditional PWM technique. Boost factor is determined by ST duty cycle and also keep it uniform to maintain the constant boost factor shown in eq (6) and eq (7).

$$D_{sh} = \frac{2 - \sqrt{3M}}{2}$$  \hspace{1cm} (6)

$$B = \frac{1}{1 - 2\frac{3n}{Ts} - \sqrt{3M-1}}$$  \hspace{1cm} (7)

The peak DC link voltage is varied from zero and peak voltage with high frequency approximately three times of the switching frequency. Out of all the PWM control schemes for ZSI network, the maximum constant boost control gives the efficient boost voltage without creating the voltage stress across the switch and ripple free inductor current flow in the network.

5. Dynamic Modeling of Induction Motor

From past the electrical vehicles (especially electric bikes) are run with using DC motors operated with dc to dc converters but by means of ac motors in electric vehicles the accuracy is improved and smooth controlling is also possible but the problem is with providing of ac source. Conventionally the ac source in electric vehicles provided by using inverters, but the problem with using normal voltage source inverters is providing input voltage high (large battery bank) this will lead to overweight and spacing problem. So, to avoid this problem, the proposed model that is Z-Source inverter is a solution [13]-[16]. In this regard, the entire control is based on shoot through conditions. For this model induction motor is used. At no load condition, induction motors draws a large current and operates with poor lagging power factor. The proposed motor drive shown in Fig.6

6. EVAnalysis

For designing of electric vehicle, we first calculate the forces acting on it. So, the total TTF [9] for a vehicle total weight (kerb weight and load weight) of 280kg’s is 4913. 18N. The torque required at wheel for corresponding wheel is

$$\tau = R_f \times TTF \times \omega_{\text{wheel}}$$

$$= 0.025 \times 4913.18 \times 0.2159$$

$$= 26.5188 \text{ N-m}$$
A. SPEED CALCULATIONS

Speed required in R.P.M for 100 KMPH speed i.e., with tolerance.

Wheel radius = 0.2159

Linear distance covered by wheel for one revolution = 2*π*r = 1.3565 m

In 1 minute the number of revolutions required to cover 1666.667 m is = 1228.6162 R.P.M

B. POWER CALCULATIONS

Power output \( P = \frac{2\pi N \tau}{60} \)

The power output is

\[ P = \tau \omega = 27 \times 136.135 = 3.675 \text{KW} \]

Motor ratings = 415 V.

Speed = 1500 rpm.

Running speed = 1228.6162 rpm.

Slip \( s = \frac{N_s - N_R}{N_R} = 0.1667 \)

So, Power required to drive the motor \( (P_{in}) \) is

\[ P_{in} = \frac{3.6756}{(1 - 0.166667)} = 4.411 \text{KW} \]

\[ = \frac{4.411 \times 1000}{746} = 5.9128 \text{HP} \]

C. CONVERTER DESIGN

Assuming the capacitors and inductors as follows

\( L_1 = L_2 = L; C_1 = C_2 = C \)

Boot factor is used for bringing the required output voltage.

\( 2V_c = B \times V_{in} \)

\( V_{in} = 96 \text{V} \)

Gain, \( G = B \times M \) Where, \( M = \text{modulation index} \)

\[ G = \frac{V_{V_{in}}}{\sqrt{2}} = 7.05929 \]

\[ B = 2G - 1 = 13.118 \]

\[ M = \frac{G}{2G - 1} = 0.538 \]

\[ 2V_c = 13.118 \times 96 = 1259.328 \text{V} \]

Boost factor and boosting value of voltage is depends on shoot through time \( (T_o) \)

Boost factor,

\[ D = \frac{T_o}{T_s} \]

Because, switching frequency is 100 KHz

\( D = 0.46188 \)

So \( T_o = 4.6188 \mu \text{sec} \)

Peak dc link voltage are calculated as

\[ V_{dc\text{link}} = \frac{V_{in}}{1 - 2D} = 1259.328 \]

\[ V_{pac} = \frac{M \times V_{in}}{2(1 - 2D)} = B \left( \frac{M \times V_{in}}{2} \right) = 338.759 \]

While the system is in shoot-through condition the switches on same leg get shorted it may leads to draw the over currents which may damage the system. The inductors provides in Z-network are limits this current to protect the system against the over currents into the system and in this condition, inductor current decreases gradually and inductor voltage becomes \( V_L = V_{input} - V_c \). So the inductor voltage becomes zero because \( V_{input} = V_c \). Finally, the inductor current is given by
Inductor  =  \( L = \frac{V_T}{\Delta I} \) H

\[ I_t = \frac{P_{th}}{V_{in}} = \frac{4411 \times 10^3}{96} = 45.9479 A \]

\( \Delta I = 10\% \) of \( I_t \)

Capacitor  , \( C = \frac{\Delta I \times T}{\Delta V} F \)

\[ = 1.0916\mu F \]

7. Simulation Results

The proposed ZSI PWM control techniques simulated with the following parameters. Resistance of three phase load- 3700W, RMS Voltage-200V, ZSI Network Inductances and capacitances are \( L_1, L_2 \& C_1, C_2 - 1.6mH \& 1091\mu F \)

Filter Inductance and Capacitance are 20mH and 2mF and Switching frequency is 10KHz with MI 0.8 for different control methods discussed in the paper. Corresponding results are elaborated for all the ZSI PWM control methods.

Fig.7 % THD of Various Control Schemes of ZSI (i) Simple Boost PWM Control (ii) Maximum Boost PWM Control (iii) Maximum Boost Third Harmonic Injection PWM Control (iv) Maximum Constant Boost PWM Control

All the PWM control schemes of proposed ZSI elaborated in this work, the corresponding harmonic distortion is analyzed by the FFT analysis and shown in Fig.7

| ZSI PWM Control Schemes | Parameters | \( D_{th} \) | G | Volt Stress | Vo | % THD |
|-------------------------|------------|-------------|--|-------------|----|-------|
| Simple Boost PWM Control |            | 0.2         | 1.33 | 1.67 | 300 | 81.17 |
| Maximum Boost PWM Control |        | 0.34        | 2.5  | 1.38 | 300 | 129.07 |
| Maximum Boost Third Harmonic Injection PWM Control | | 0.34 | 2.5 | 1.38 | 300 | 121.42 |
| Maximum Constant Boost PWM Control | | 0.31 | 2.1 | 1.26 | 312 | 66.38 |
From Table 3, various parameters are analyzed by keeping the Modulation Index M is 0.8 for all the PWM control schemes of ZSI. Out of all the control techniques, Maximum Boost control gives the efficient performance by reducing stress across the switch, with less % of THD and desirable peak output voltage.

Fig. 8 shows that source voltage, capacitor voltage and DC link Voltage of ZSI network. The DC link voltage is boosted 100V, it seen that from 400V to 500V the proposed ZSI converter capacitor voltage compare with maximum output voltage of input voltage. It is observed that Fig. 9 proposed inverter phase voltage is around 388V and Line voltage is boosted to 500V.

Fig 10 and 11 shows that output line voltage and current of proposed ZSI network controlled with Simple boost PWM Control and Maximum Constant Boost control respectively. It is observed that the output line voltage and current in Simple Boost Control is 213.04V and 15.01A. However, in Maximum Constant Boost control, 224.5V and 16.64A. These results are obtained by maintaining the Modulation Index 0.8. Hence it can be concluded that compared to the Simple Boost Control, the output line voltage and current is enhanced by using Maximum Constant Boost control.
The proposed ZSI fed Asynchronous Motor Load Torque and Rotor Speed as shown in Fig.12. Load torque varies from 5 N-m to 12.5 in first step, 12.5 to 25 N-m and 25-35 N-m, correspondingly the rotor speed and DC link voltage is varied accordingly shown in Fig 13.
When step change in Load Torque, the Dc link Voltage, Peak undershoot and settling time is measured and shown in Table 4.

**Table 4 Various Parameters w.r.t Step change in Load Torque**

| Parameters                             | 5Nm -12.5Nm | 5Nm -12.5Nm | 5Nm -12.5Nm |
|----------------------------------------|-------------|-------------|-------------|
| Percentage of Peak undershoot (%)      | 11.1        | 18.6        | 15.3        |
| Settling Time(Sec)                     | 0.25        | 0.32        | 0.29        |
| Dc Link Voltage from 600V(V)           | 585         | 567         | 550         |

7.1. Acceleration and Deceleration modes of proposed EV w.r.t change in Speed of the ZSI fed Asynchronous Drive

The proposed ZSI fed Asynchronous Motor Load Torque and Rotor Speed as shown in Fig.14 when step change in Speed. Change of Dc Link voltage w.r.t the step change in Speed as
shown in Fig.15. At starting, in acceleration mode, with 25Nm torque, the drive is operated and it is constant for both acceleration and deceleration modes of operation. If speed, increases from reference speed 750rpm to 1000rpm, due to overshoot of the step change in speed, correspondingly dc link voltage is reduced. Speed increases from 1000rpm to 1400rpm further, the dc link voltage is still decreased. In deceleration mode, speed decreases from 1400rpm to 1000rpm, now slowly voltage is increased and again set back to the reference speed 750rpm. The results are tabulated in Table.5

![Fig.14 Proposed ZSI fed Asynchronous Motor(i) Shaft Torque (ii) Rotor Speed](image1)

![Fig.15 Proposed ZSI fed Asynchronous Motor w.r.t change in Speed](image2)

| Parameters                        | Step change in Speed of proposed ZSI fed Asynchronous Motor Drive |
|-----------------------------------|---------------------------------------------------------------|
| Percentage of Peak Overshoot/undershoot (%) | 750rpm - 1000rpm | 1000rpm - 1400rpm | 1400rpm - 1000rpm | 1000rpm - 750rpm |
|                                   | 5                | 6.8               | 5.6                | 4.8                |
| Dc Link Voltage from 600V(V)     | 569              | 532               | 919                | 785                |

8. Conclusions
Proposed ZSI inverter is having unique feature and overcome the drawbacks of classical voltage and current source inverters. There are four PWM control methods are discussed with same modulation index 0.8. The parameters like voltage gain (G), Voltage stress (Vs), Boost factor (B) and ST duty ratio (Dsh) are analyzed and compared for all the PWM control schemes. Voltage stress is reduced and improve boost factor obtained by Constant Boost control method with less inductor value. The ZSI fed to asynchronous drive is simulated and speed variations are tabulated with constant load torque 25Nm. DC link voltage is varied w.r.t the speed or load change. The proposed converter efficiently used for EV both in acceleration and deceleration modes of operation. All the results are simulated in the MATLAB/Simulink environment. Analysis of EV is presented with proposed drive. The proposed ZSI have high efficient with good performance, cost effective and used with lesser components.

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