PERFORMANCE EVALUATION OF THREE-PHASE INDUCTION MOTOR DRIVE FED FROM Z-SOURCE INVERTER

Bindeshwar Singh*, S. P. Singh*, J. Singh#, and Mohd. Naim#

***Abstract*—This paper presents a Z-source inverter which has been proposed as an alternative power conversion concept for adjustable speed AC drives. It is having both voltages buck and boost capabilities as they allow inverters to be operated in the shoot through state. It utilizes an exclusive Z-source network (LC component) to DC-link in between main inverter circuit and the DC source (rectifier). By controlling the shoot-through duty cycle, the inverter system using IGBTs, reduces the line harmonics, improves power factor, increases reliability and extends output voltage range. The proposed strategy reduces harmonics, low switching stress power and low common mode noise.**

***Index Terms*—Induction motor drive, pulse width modulation (PWM), shoot-through state, Z-source inverter.**

I. INTRODUCTION

Z-SOURCE inverter based induction motor drives provides a low cost and highly efficient two stage structure for reliable operation. It consists of voltage source for the supply of rectifier section and impedance network such as their equivalent behaviour as two equal inductors and two equal capacitors, three-phase inverter, and a three-phase induction motor. The rectification of AC voltage is done by rectifier section to obtain DC voltage for further supply. The rectifier output DC voltage is now fed to the impedance network. The network inductors are connected in series arms and capacitors are connected in diagonal arms as shown in Fig.1. Depending upon the boosting factor capability of impedance network the rectified DC voltage is buck or boost upto the voltage level of the inverter section (not exceed to the DC bus voltage) [1]. This network also acts as a second order filter and it should be required less number of inductor and capacitor.

This paper presents an efficient PWM based Z-source inverter approach for the control of adjustable speed drive employing poly-phase induction motor. 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 the same phase leg.

Shoot through mode allows simultaneous conduction of devices in same phase leg. Therefore, on behalf of boost factor of DC-link, a Z-source inverter can boost or buck to the voltage to a desired output voltage that is greater / lesser than the DC bus voltage [2].

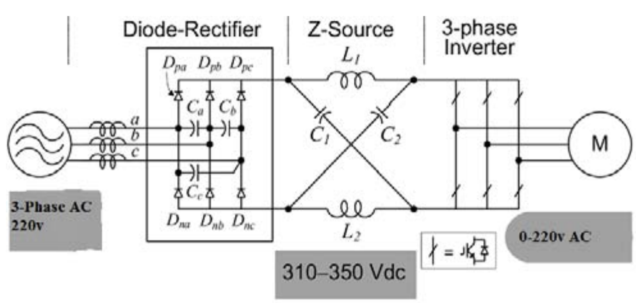

Fig. 1 Main circuit configuration of proposed Z-source inverter ASD system

The unique feature of the Z-source inverter is that the output AC voltage can be any value between zero and infinity regardless of DC voltage. However, three phase Z-source inverter bridge has one extra zero state when

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the load terminals are shorted through both the upper and lower devices of any one phase leg, any two phase legs, or all three phase legs. This shoot-through zero state is forbidden in the traditional voltage source inverter, because it would cause a shoot-through. The Z-Source network makes the shoot-through zero state efficiently utilized throughout the operation [3].

Since the Z-source Inverter Bridge can boost the capacitors such as C_1 and C_2, voltages to any value that is above the average DC value of the rectifier, a desired output voltage is always obtainable regardless of the line voltage. Here inverter bridge switching is provided by pulse width modulation generator.

II. Z-SOURCE CONVERTER

Many significant problems that occur in the conventional inverter (fig. 2 (a) & (b)) result from their operating principle. These problems are connected to the following disadvantage:

- In case of voltage source inverter (Fig. 2(a)): output voltage $V \leq V_{dc}/ 1.73$; voltage regulation-only decreasing; problems with short circuits in problems.
- In case of current source inverter (Fig. 2(b)): output voltage $U_m \geq U_{dc}/ 1.73$; voltage regulation-only increasing; difficult to apply conventional modular IGBT and open circuits problem.

The issues with short circuits in branches and open circuits are connected with vulnerability of inverter to damages from EMI distortion if the inverter applications require amplitude to be adjusted outside the limited region, output transformer or additional DC/DC converter Fig. 2(a) & (b), can be used.

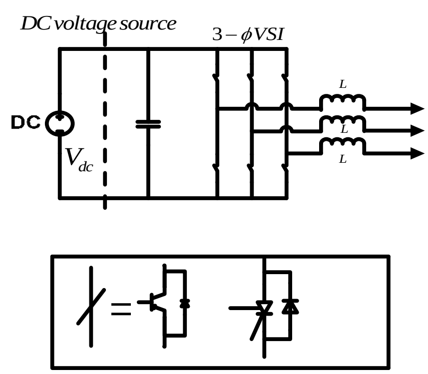

Fig.2 (a) conventional inverter system VSI mode

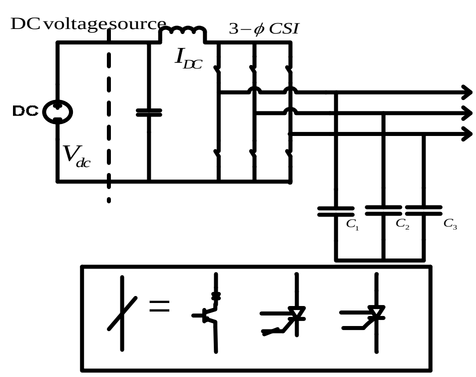

Fig.2(b) conventional inverter system CSI mode

Disadvantage of the solutions with output transformer (Fig. 2(a)) are most of all range overall dimensions, heavy weight and range of regulation limited by transformer voltage ratio. However, if an additional DC/DC converter is applied (Fig. 2(b)), then it results in two stage conversion of the electrical energy, and there for we should higher costs of the system and increased losses. Morever, in such a case, one type of inverter cannot be replaced by another (i.e. CSI cannot be replaced by VSI and vice versa) and short circuits or open circuits and transition processes occur. Therefore, the search continues for new solution in inverter system with improved adjustment properties. Especially worth attention seem to be the z-source inverter patented by F.Z. Peng in literatures [4]-[5].

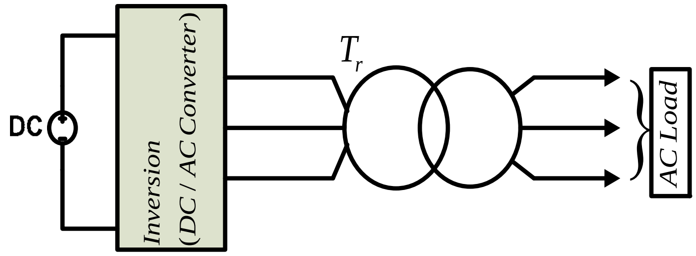

Fig. 3(a). The inverter system with increased range of voltage regulation

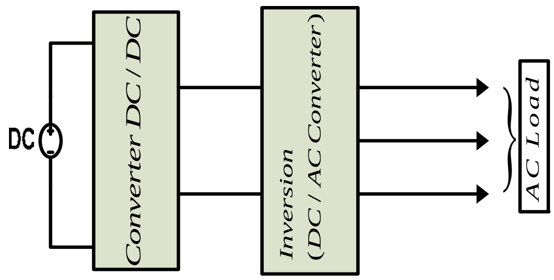

Fig. 3(b). The inverter system with increased range of current regulation.

Fig. 3(a) & (b) presents basic schemes of the three phase z-source inverter: voltage (Fig. 3(a)) and current (Fig. 3(b)) [4]-[5]. In contrast conventional VSI and CSI inverter, on the dc side of the z-source inverter is a D diode and Z-source of ‘‘X’’ shape, composed of the two capacitors C_1 and C_2 and two chokes L_1 and L_2. The diode prevents forbidden reversed current flow (for voltage z-inverter) or reversed voltage (for current z-source inverter). For this reason, application of the basic z-source inverter are possible only it energy return to the input source is unnecessary. Further, this is forbidden in the case of a fuel cell or photovoltaic cell. It should be noted that the same diode function can be saved by other PE system as well. The main advantages of the z-source inverter are:

- Secures the function of increasing and decreasing of the voltage in the one step energy processing (lower costs and decreased losses);
- Resistant to short circuits on branches and to opening of the circuits that improve resistant to failure switching and EMI distortions;
- Relatively simple start-up (lowered current and voltage surges).

We should acknowledge that two-direction energy flow is only possible due to change of a diode of the source on the switch of the inverter. Because the operation principle of the voltage and current z-source inverter is similar, all the solution considered below relate only to the voltage z-source inverter.

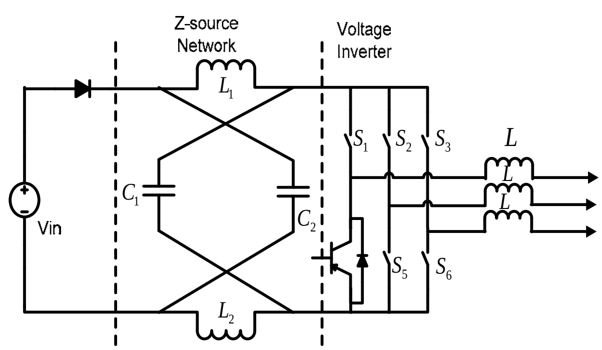

Fig. 4(a) Basic schemes of the z-source inverter **voltage**

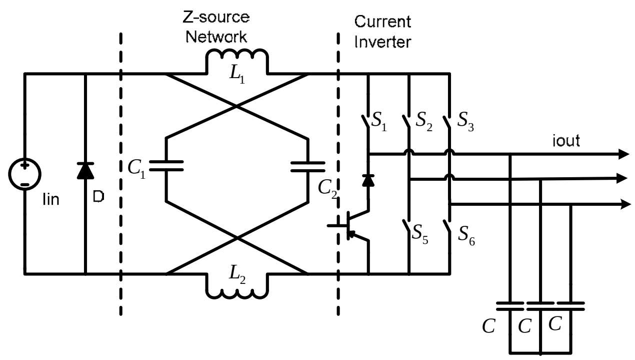

Fig. 4(b) Basic schemes of the z-source inverter **current.**

A). Operation Principle Of The Voltage Z-Source Inverter

Conventional three-phase VSI system (Fig. 1(a)) can assume eight states: six active states (while exchange of instantaneous power between the load and DC circuits) and two null states (when the load is shorted by transistors). Whereas, three phase z-source inverter (Fig. 4(a)) can assume nine states, that is one more than in the VSI system- the additional nine state is the third 0 state, occurring when the load is shorted simultaneously by lower and upper groups of transistors. This state is defined as ‘‘shoot through’’ state and may be generated in seven different ways, although of equivalent procedures; independently through every branches (three procedures), simultaneously through two of the branches (three procedures), and simultaneously through all the three branches (one procedures). The main and unique characteristics of the z-source inverter are that above the voltage V_{in}.

Fig. 5 (a) & (b) describes simple equivalent schemes of the z-source inverter examined from the clap site of DC, where a source V_d is modeling inverter s_1-s_6. In the shoot through state (Fig. 5(a)) a D diode is polarized reversely and does not conduct the inverter bridge input voltage $V_d = 0$, and energy stared in capacitor. C is transferred to chokes L. In ‘‘non-shoot through’’ states (Fig. 4(b)), where every combination of the switches S_1-S_6 that is allowed in VSI system is also possible, the diode D conducts and the voltage V_d increases stepwise from 0 to its maximum V_d^*.

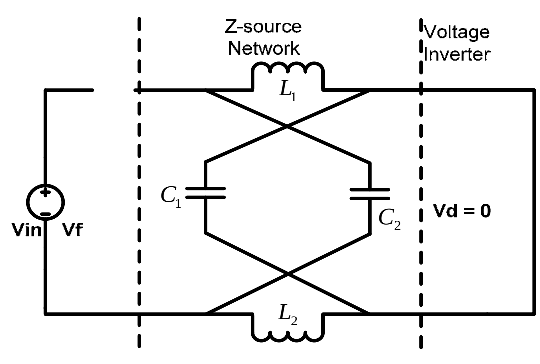

Fig. 5(a) Equivalent schemes of the z-source inverter ‘‘shoot through’’

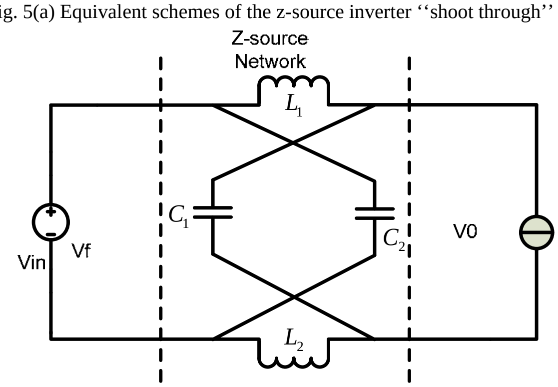

Fig. 5(b) Equivalent schemes of the z-source inverter ''non-shoot through'' states.

Science z-source are symmetric circuits (Fig. 5(a) & (b)), when $C_1 = C_2$ and $L_1 = L_2$ and low voltage pulsation V_{C1} and V_{c2} during pulse period T,

$$V_{c1} = V_{c2} = V_c \quad and \quad V_{L1} = V_{L2} = V_L \qquad (1)$$

Where V_c is average value of voltage in capacitor, V_L-instantaneous voltage in chokes. Considering equation (1) and equivalent schemes of the z-source inverter (Fig. 5(a) & (b)), voltage V_d is calculated on the basis of following dependencies in ''shoot through'' state (Fig. 5(a)) duration T_z.

$$V_L = V_C, \quad V_f = 2V_C \quad V_d = 0 \qquad (2)$$

In ''non-shoot through'' states (fig. 4b) duration T_N,

$$\left.\begin{aligned} V_L &= V_{IN} - V_C, \\ V_f &= V_{IN} \\ V_d &= V_C - V_L = 2.V_C - V_{IN} \end{aligned}\right\} \qquad (3)$$

Where V_f is Z-source input voltage

Assuming that in a pulse period $T = T_Z + T_N$, in a steady state the average voltage in chokes $V_L = 0$ on the basis equation (2) and (3), we should conclude.

$$V_L = \frac{1}{T}\left(\int_0^{T_z} v_l\, dt + \int_{T_z}^{T} v_l\, dt\right) = \frac{T_Z.V_C + T_N.(V_{IN} - V_C)}{T} = 0 \qquad (4)$$

Hence, average input voltage of the inverter bridge input voltage

$$V_C = V_d = V_{IN}.\frac{T_N}{T_N - T_Z} = V_{IN}\frac{1-D}{1-2D} \qquad (5)$$

Where $D = T_Z/T$ is ''shoot through'' duty factor, satisfying a requirement $D<0.5$. Similarly on the basis of equation (3) – (5), the value of voltage V_d in ''non-shoot through'' is determined

$$V_d^* = V_C - V_L = 2.V_C - V_{IN} = V_{IN}.\frac{1}{1-2D} = V_{IN}.B \qquad (6)$$

Where

$$B = \frac{1}{1-2.D} = \frac{T}{(T_N - T_Z)} \geq 1$$

Is a peak factor, and the value V_d^* is determined by relative voltage V_{IN}.

Further, the value V_d^*. Determined output voltage amplitudes $V_{out(max)}$ of the Z-source. When applying sinusoidal PWM the amplitude equals.

$$V_{out(\max)} = M.\frac{V_d^*}{2} = \frac{M}{1-2.D}.\frac{V_{IN}}{2} = K.\frac{V_{IN}}{2} \qquad (7)$$

Where M is modulation index, of maximum values limited by inequity $M \leq 1-D$. related to time T_z of ''shoot through'' states. As we concludes, based on equation (7), the Z-source inverter output voltage amplitude $V_{out(max)}$ can be either lower or higher in typical VSI system with sinusoidal PWM, e.g. $V_{out(max)} = M.V_{in}/2$.

This possibility is advantage when locking of the discharge of the function.

$$K = \frac{M}{(1-2.D)} \qquad (8)$$

The discussed properties of the voltage Z-source inverter are confirmed by research presented in a numbers of publications from the recent post in ref. [6]-[7].

III. PWM CONTROL TECHNIQUE

PWM inverters can be classified such as single phase and three-phase. These inverters are capable of producing AC voltages of variable magnitude as well as variable frequency. The PWM inverters are very commonly used in adjustable speed AC motor drive where one needs to feed the motor with variable voltage, variable frequency supply. For wide variation in drive speed, the frequency of the applied AC voltage needs to be varied over a wide range. The applied voltage also needs to be varied almost linearly with the frequency. Carrier-based PWM methods are preferred in implementing modulators for inverters as they are simple and easy to realize as shown in Fig. 6 and generation of switching signals with interleaved carrier-based PWM is shown in Fig. 7.

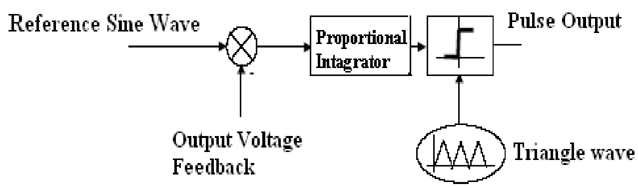

Fig. 6. PWM Pulse Generation Circuit.

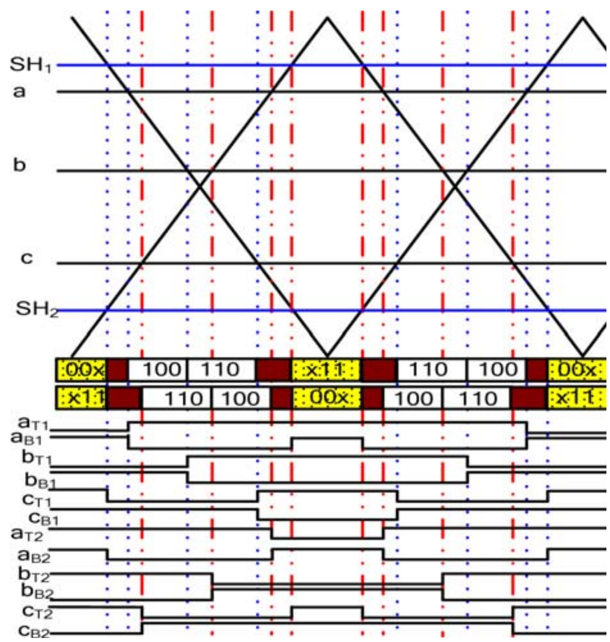

Fig. 7. Generation of switching signals with interleaved carrier-based PWM.

There are two possibilities in deriving the modulation signals. The first and obvious method is to modulate the two inverters from a common carrier signal with careful insertion of shoot-through time with simple boost or minimum switching methods proposed in references [8]-[9] for a single *Z*-source inverter. This pulse is used to switch ON or OFF the power switches. The width of the pulse or duty cycle can be varied by varying the frequency of the reference wave.

III. SIMULATION RESULTS AND DISCUSSION

Fig. 8 shows the main circuit configuration of the Z-source fed PWM induction motor drive, similar to that of the traditional ASD system. The Z-source ASD system's main circuit consists of three parts: a diode rectifier, DC link circuit and Inverter Bridge.

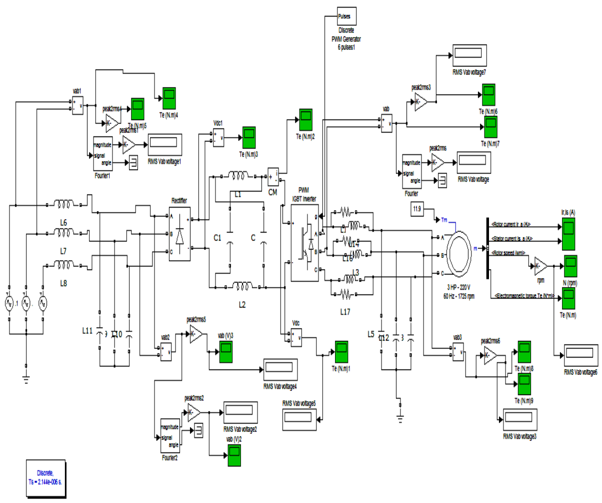

Fig. 8. Simulink model for Z-source fed PWM IM drive.

Different cases are considered for showing the parameter variation in the value of load torque.

Case 1: Full load, *(T_{fl} = 11.9N-m)*
Case 2: Under load condition, *(T_{ul} = 8 N-m)*
Case 3: No-load condition, *(T_{fa} =0 N-m)*
Case 4: Step load condition, *(T_{sl} =8-11.9 N-m)*
Case 5: Overload condition, *(T_{ol} =16 Nm)*

Case-1) Response of Induction motor for full load (T_{fl} = 11.9N-m)

Fig. 9 shows the waveforms of DC-link voltage of Z-source fed PWM induction motor drive. Here DC-link voltage is boosted to 309 V due to Z-source. The DC link voltage is roughly equal to 1.38 times the line voltage is equal to 220 V. Transients in stator and rotor currents are there for short span of time that is it settles quickly as shown in Figs. 10-12.

The starting current is high but within the range of 1.16 second, it reaches to steady state value. Steady state value of stator current is equal to 13.4 Ampere. Steady state value of rotor current is equal to 13.10 Ampere. The result for the speed estimation are shown in Fig. 8. It can be observed that speed reaches at steady state value that is 1718 rpm with in 1.09 second when motor is subjected to constant load of 11.9 N-m. So when the motor is fed by Z-source inverter then its speed increases and settling time decreases and it is due to voltage after inverter circuit which boosted to 218 V by Z-source inverter. The electromagnetic torque waveform of the induction motor is shown in Fig. 13.

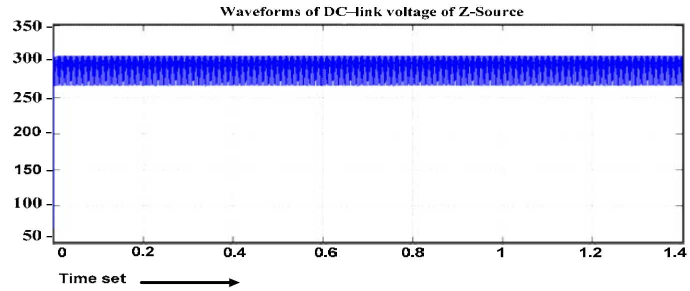

Fig. 9. Waveforms of DC–link voltage of Z-Source.

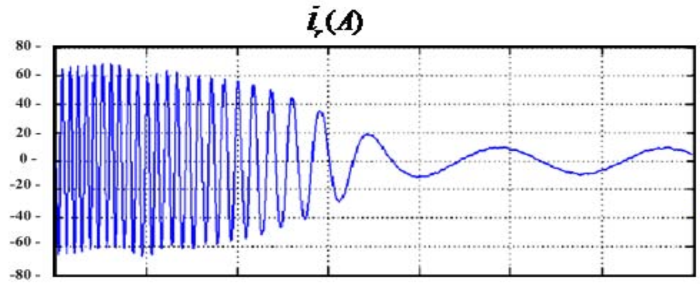

Fig. 10. Rotor current/phase i_r under full load condition i_r=19.06A.

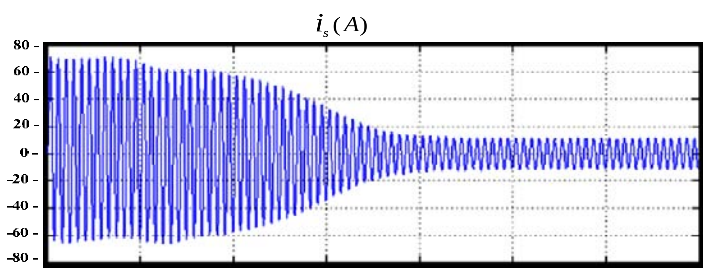

Fig. 11. Stator current/phase i_s under full load condition i_s =17.09A.

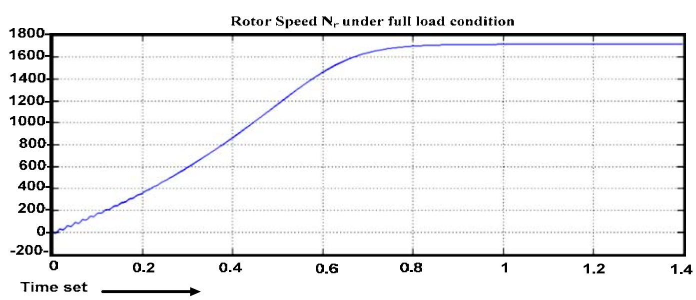

Fig. 12. Rotor Speed N_r under full load condition ns=1714, ts=0.89

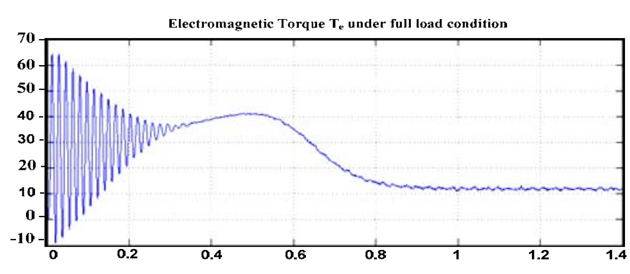

Fig. 13. Electromagnetic Torque T_e under full load condition.

Case-2) ***Response of Induction motor for under load condition ($T_{under\ load}$ = 8 N-m)***

It can be observed that speed reaches at steady state value that is 1745 rpm with in 0.714 second when motor is subjected to constant load of 8 N-m. So when the motor is fed by Z-source inverter then its speed increases and settling time decreases.

Also the waveform for rotor speed, input voltage, per phase rotor current, per phase stator current and also the waveform of electomagnetic torque is shown in Figs. 13-17.

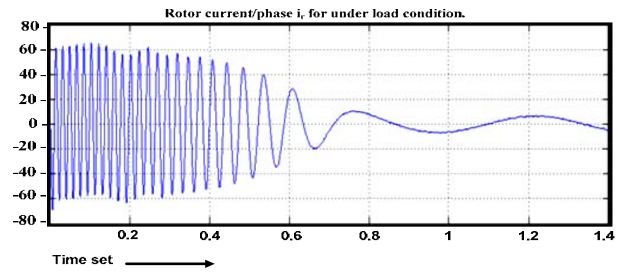

Fig. 14. Rotor current/phase i_r for under load condition.

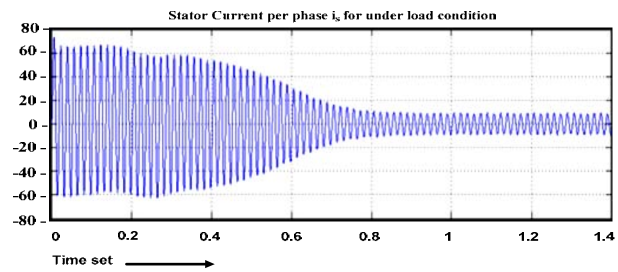

Fig. 15. Stator Current per phase i_s for under load condition.

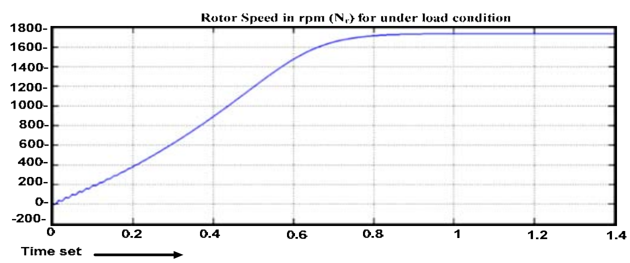

Fig. 16. Rotor Speed in rpm (N_r) for under load condition.

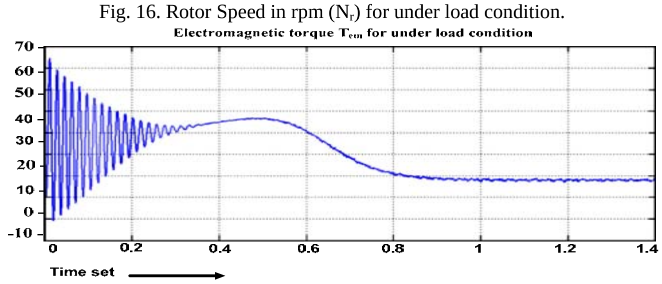

Fig. 17. Electromagnetic torque T_{em} for under load condition.

Case-3) Response of Induction motor at No load condition (T_{nl} =0 N-m)

It can be observed that speed reaches at steady state value that is 1799.4 rpm with in 0.736 second when motor is subjected to no load. So when the motor is fed by Z-source inverter then its speed increases and settling time decreases.

Also the waveform for rotor speed, input voltage, per phase rotor current, per phase stator current and also the waveform of electomagnetic torque is shown in Figs. 18-21.

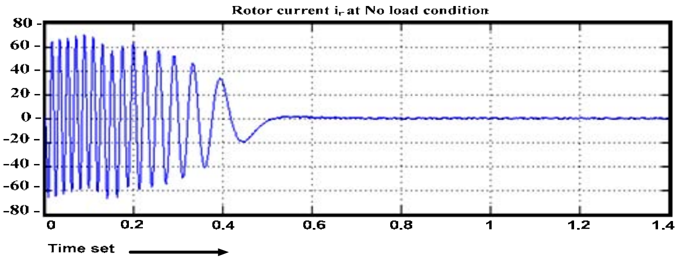

Fig. 18. Rotor current i_r at No load condition.

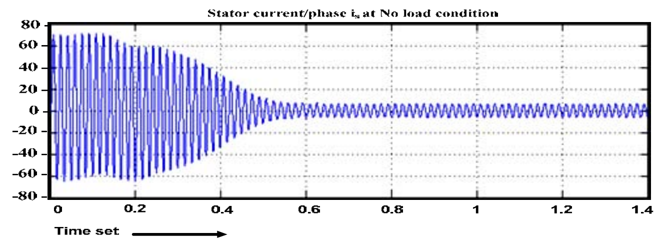

Fig. 19. Stator current/phase i_s at No load condition.

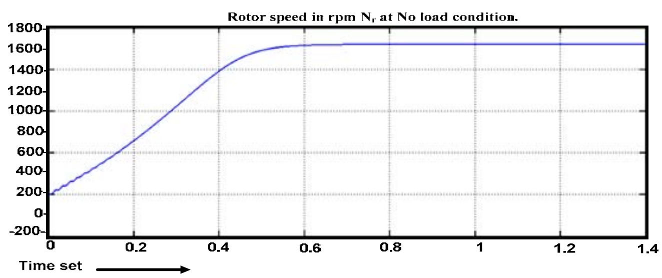

Fig. 20. Rotor speed in rpm N_r at No load condition.

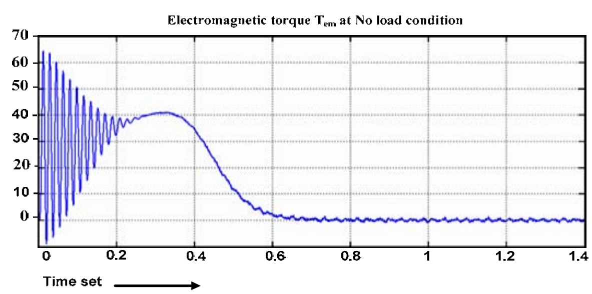

Fig. 21. Electromagnetic torque T_{em} at No load condition.

Case-4) Response of Induction motor at Step load condition (T_{sl} =8-11.9 N-m)

It can be observed that speed reaches at steady state value that is 1745 rpm with in 6.25 second and constant till upto 1 second and than decreases to obtain the speed of 1718 rpm within the range of 1.25 second, when motor is subjected to step load in the range of 8-11.9 N-m. So when the motor is fed by Z-source inverter then its speed increases and settling time decreases. Also the waveform for rotor speed, input voltage, per phase rotor current, per phase stator current and also the waveform of electomagnetic torque is shown in Fig. 22-25.

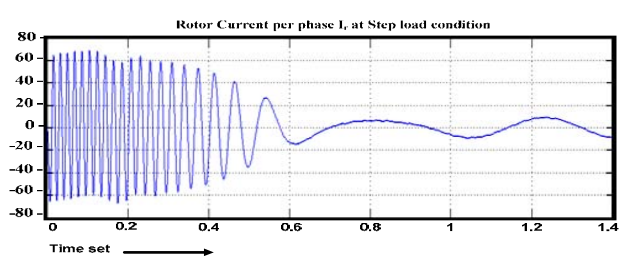

Fig. 22. Rotor Current per phase I_r at Step load condition. I_r=15.9A

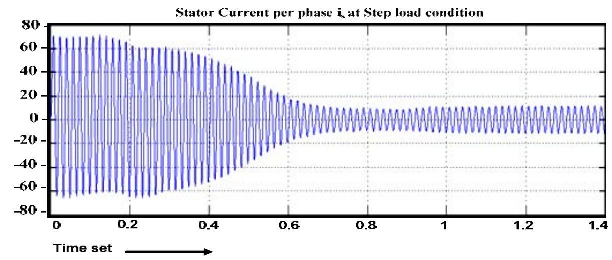

Fig. 23. Stator Current per phase i_s at Step load condition i_s =15.07A

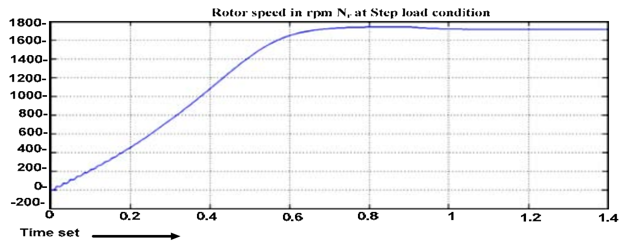

Fig. 24. Rotor speed in rpm N_r at Step load condition N_r= 1718, ts= 1.27s

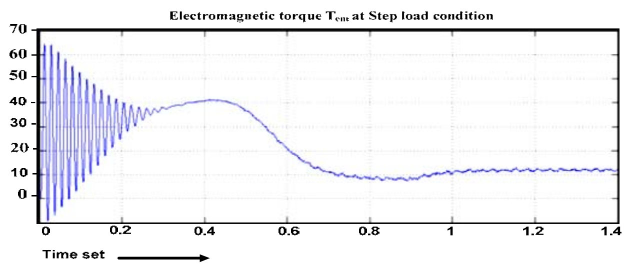

Fig. 25. Electromagnetic torque T_{em} at Step load condition.

Case-5) Response of Induction motor at overload condition ($T_{over\ load}$ =16 N-m)

It can be observed that speed reaches at steady state value that is 1618 rpm with in 1.035 second when motor is subjected to constant load of 16 N-m. So when the motor is fed by Z-source inverter then its speed increases and settling time decreases.

Also the waveform for rotor speed, input voltage, per phase rotor current, per phase stator current and also the waveform of electomagnetic torque is shown in Figs. 26-29.

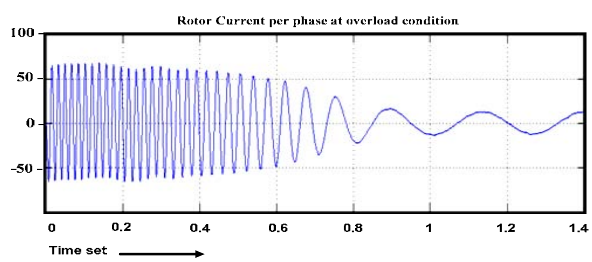

Fig. 26. Rotor Current per phase at overload condition i_r =22.15A

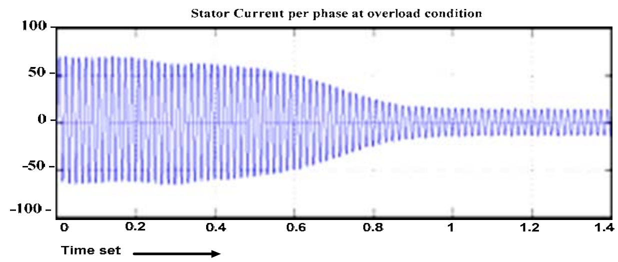

Fig. 27. Stator Current per phase at overload condition i_s =22.45A

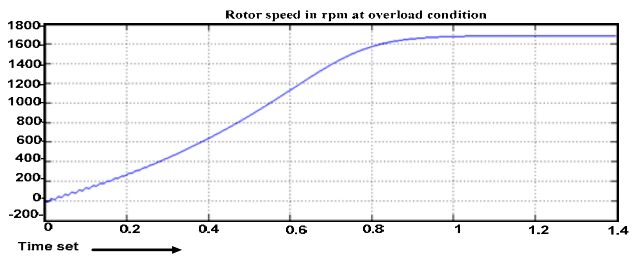

Fig. 28. Rotor speed in rpm at overload condition N_r =1618 rpm, 1.035s

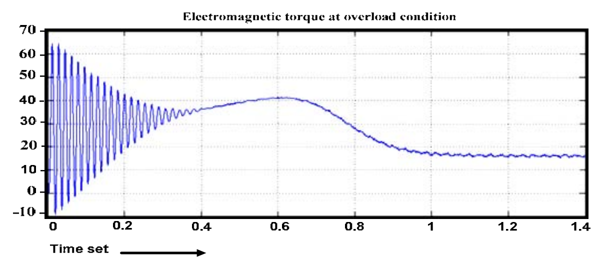

Fig. 29. Electromagnetic torque at overload condition

IV. CONCLUSION

In this paper, three-phase induction motor with Z-source inverter was discussed and simulated in SIMULINK/MATLAB toolbox. The performance parameters of 3-phase induction motor such as rotor current, stator current, rotor speed, and electromagnetic torque was investigated for the different load conditions. Finally it is concluded that the proposed scheme of three-phase induction motor drive with Z-source and PWM technique is fast enough and leads to a satisfactory operation in open loop systems.

APPENDIX

Motor Specification: 3 hp, 220V, 60 Hz, 4 pole, 1725 rpm
Simulation parameters for Z-source are given as follows:

$L_1 = L_2 = (100e\text{-}9)$ H
$C_1 = C_2 = (1000e\text{-}6)$ F

V. REFERENCES

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