ISSN: 0976-3104
SUPPLEMENT ISSUE

ARTICLE OPEN ACCESS

ANALYSIS OF A SPEED CONTROL SYSTEM OF INDUCTION MOTOR FED BY A Z-SOURCE INVERTER BASED ON V/F SCALAR CONTROL

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ABSTRACT

This paper proposes a closed loop speed control of an induction motor fed by a Z-source inverter (ZSI), the speed control is based on V/F scalar control. ZSI is a one-stage power conditioner that employs a capacitor-inductor network for connecting inverter to the DC source. In this paper, through addressing detailed dynamic modeling of ZSI , ZSI is used for connecting the DC source to a induction motor. A closed loop controller is designed to control the peak dc link voltage of the ZSI, where the peak dc-link voltage is estimated by measuring the input and the capacitor voltages. By using the dynamic model of ZSI, the proper controller for the DC side is designed. The proposed speed control system compared with the standard adjustable speed drives (ASD), are able to change the motor speed from zero to the rated speed with the rated load torque. Also the ZSI inverter system provides ride-through capability during voltage sags, reduces line harmonics, improves power factor and reliability, and extends output voltage range. Simulation results are provided to demonstrate the competence of the system.

Published on: 25th– Sept-2016

KEY WORDS

Index Terms- Z-source Inverter, shoot through state, V/F scalar control.

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INTRODUCTION

Induction motors have many advantages compared to DC motors and synchronous motors in many aspects, such as size, efficiency, cost, life span and maintainability. Low cost and ease of manufacturing have made the induction motors a good choice for electric and hybrid vehicles [1]. However, one must be able to achieve energy regenerative braking and be able to control the torque and the speed of an induction motor in traction drives such as hybrid electric vehicles [2]. The application of adjustable-speed drives (ASD's) in commercial and industrial facilities is increasing due to improved efficiency, energy savings, and process control. The traditional adjustable-speed drives system is based on the voltage-source inverter, which consists of a diode rectifier frond end, dc link capacitor, and inverter bridge. It suffers some common limitations and problems. 1) Obtainable output is limited quite below the input line voltage, 2) Voltage sags can interrupt an ASD system and shut down critical loads and processes; 3) Performance and reliability are compromised by V-source inverter structure[3].

Z-source inverter (ZSI) is known as a single-stage buck/boost inverter [4]. **[Figure- 1]** shows the general structure of Z-source Inverter. With an impedance network coupling the inverter main circuit to the dc source, the ZSI achieves voltage buck/boost in one stage, without introduce more switching devices. Shoot-through state enables energy to be stored in inductors, which is released when at non-shoot-through state, followed by the voltage boost feature. For the voltage-fed type ZSI (abbreviated as ZSI), voltage boost methods based on pulse-width modulation have been firstly investigated as simple boost control, maximum boost control and maximum constant boost control [5, 6]. Because of its single-stage voltage buck/boost properties, the ZSI can deal with input voltage fluctuation in a wide range, which is conventionally achieved by a two-stage DC-DC cascaded by DC-AC structure.

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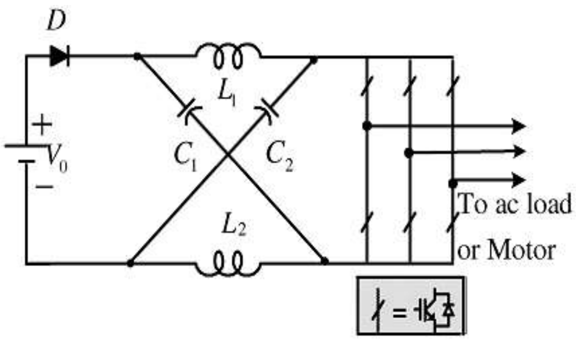

Fig:1. General structure of the ZSI

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The volts per hertz (V/F) induction motor drives with inverters are widely used in a number of industrial applications leading not only to energy saving, but also to improvement in productivity and quality. The low cost applications usually adopt V/F scalar control when no particular performance is required. Variable speed pumps, fans and appliances are the examples. Furthermore, these applications usually do not require zero speed operation. The main advantage of V/F control is its simplicity and for this reason it has been traditionally implemented using low cost microcontrollers [7].

This paper presents V/F control based closed loop speed control of a three phase induction motor fed by ZSI. The dynamic model of the asymmetric Z-source network is constructed by small signal analysis. The peak dc link voltage is estimated by measuring the input and the capacitor voltages. A closed loop controller is designed based on the dynamic model of the ZSI for controlling the peak dc link voltage. MATLAB Simulation results are included to prove the concept and demonstrate the features of the proposed ASD system.

Dynamic Modeling of Z-Source Network

Fig. 2 shows the general structure of the voltage-fed type Z-source network. .Since there is inductor L_1 at the input of the two-port impedance network, the input current of the Z-Source network is continuous. The employed Z-source network couples the converter to the voltage source, load, or another converter. The voltage source can be one or a combination of follows: a battery, photovoltaic panel, fuel cell, diode rectifier, a capacitor or an ac voltage source, etc. Switches involved in the Z-Source network can be unidirectional for single- direction power flow or bidirectional for dual-direction power flow. For the output of the ZSI, there can be passive load or source, either in dc or ac form, which is commonly coupled by the smooth inductor [8].

The buck operation is normally accomplished by conventional switch of the converter, where S_2 is equivalently OFF and S_1 is ON. Taking a voltage-fed Z-Source network as an example, the OFF state of S_2 implies none of the inverter phase legs is shorted. In steady state we have The output voltage of Z-Source network depends on the switching duty cycle of the conventional converter. The boost operation can be achieved by introducing shoot-through states into switch S_2,e.g. S_2 is ON in a short interval T_0 of one switch duty cycle T_s. Accordingly switch S_1 is OFF either due to the circuit (for example a diode is used as S_1) or active control. By defining the shoot-through duty ratio $d_0=T_0/T_s$, we have following voltage equations of the Z-Source network in steady state:

$$v_{C1} = v_{C2} = \frac{1-d_0}{1-2d_0} v_{in} \qquad (1)$$

$$\hat{v}_s = v_{C1} + v_{C2} = \frac{1}{1-2d_0} v_{in} = Bv_{in} \qquad (3)$$

where $\hat{v}_s$ is the peak voltage of the Z-Source network output; and B is defined as the voltage boost factor.

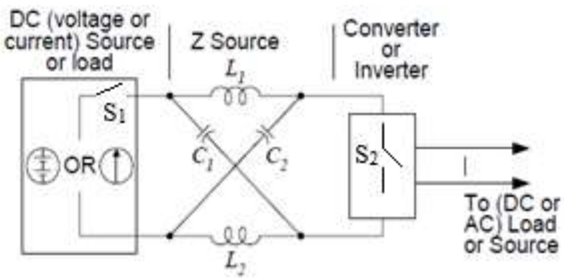

Fig:2. Structure of the voltage-fed type Z-source network

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When operating at shoot-through states, the ac load terminals are shorted through both upper and lower devices of any phase leg(s); therefore the single switch is ON and the equivalent circuit of the ZSI is shown as **[Figure- 3]**. When operating at non-shoot-through states (i.e. six active states and two conventional zero states where either all the upper devices or all the lower devices are gated on) the single switch is OFF and the equivalent circuit of the ZSI is shown as **[Figure- 4]**.. Considering the asymmetric Z-source network, there are four state variables: the current through two inductors i_{L1}, i_{L2}; the voltage across the capacitors v_{C1}, v_{C2}. For general analysis purpose, input voltage *vin*is chosen as system input, to which input current *i_{in}*is related. The relationship of *v_{in}*and *i_{in}* will be determined by specified energy source nature. Independent load current i_{laod} serves as another input (disturbance) of the quasi-Z-source network. Choose v_{C1} and i_{L1} (= i_{in}) as the output of the studied system. Forsimplification, assume that $C = C_1 = C_2$, $L = L_1 = L_2$, the stray resistances of inductors $r = r_1 = r_2$, the equivalent series resistances (ESR) of capacitors $R = R_1 = R_2$.

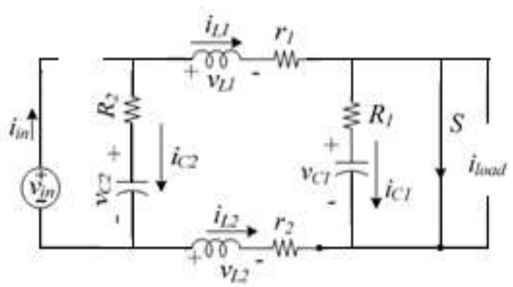

Fig:3.: Equivalent circuit of quasi Z-source network when in the shoot-through

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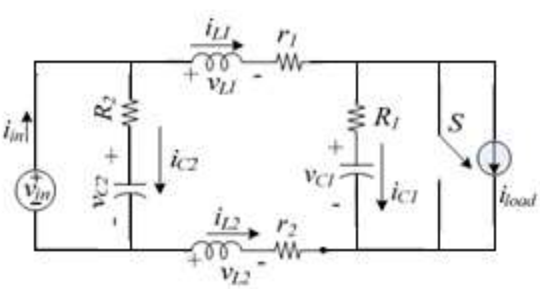

Fig:.4. Equivalent circuit of quasi Z-source network when in the non-shoot-through states

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To obtain the small signal model of ZSI, it is necessary to write the dynamic state equations of ZSI in both shoot-through and non-shoot-through states separately. By using state space averaging and applying perturbation to dynamic state variables, the Z-source network small signal dynamics can be model. Eventually the Laplace-transformed transfer functions of the multi-input multi-output Z-source network can be derived. Assuming any two of the system inputs to be zero, one can get small signal transfer functions from the remaining to the state variables. According to the small-signal model, the transfer functions from d_0 *to* capacitor voltage v_{C1} and v_{C2} are identical, denoted as $\mathbf{G}^{\mathbf{v_C}}_{\mathbf{d_0}}\,(\mathbf{s})$ in (4), where V_C, I_L, I_{load} and D_0 are presented an operating point.

$$G_{d_0}^{v_C}(s) = \frac{(2V_C - V_{in} - RI_{load})(1-2D_0) + (I_{load} - 2I_L)(Ls + R + r)}{LCs^2 + C(r+R)s + (1-2D_0)^2}$$

Also The transfer functions from d_0 to inductor current i_{L1} and i_{L2} are identical, denoted as $G_{d_0}^{i_L}(s)$ in (5).

$$G_{d_0}^{i_L}(s) = \frac{(2V_C - V_{in} - RI_{load})Cs - (I_{load} - 2I_L)(1-2D_0)}{LCs^2 + C(r+R)s + (1-2D_0)^2} \quad (5)$$

Controller Design for Closed Loop V/F Controlled Induction Motor

A simplified diagram of the V/F controlled induction motor is shown in **[Figure- 5]**. The closed loop control by slip regulation of the combined inverter induction motor improves the dynamic performance. The speed loop error generates the slip command ω_{sl}^* through a proportional integral (PI) controller and a limiter. The slip is added to the speed feedback signal to generate the slip frequency command ω_e^*.Thus the frequency command generates the voltage command through a Volts/Hz generator [7].

The shoot through duty cycle d_0 and modulation index M are generated by dc side and ac side controllers of ZSI. Control of dc side and ac side of the ZSI is executed separately. **[Figure- 6]** shows the control scheme of dc side of the ZSI. Pulses generated by the dc-side controller (for voltage boost or buck) and the ac side controller (for dc-ac conversion) are combined together by logical 'OR' to fire six IGBTs, assuming '1' is ON and '0' is OFF.

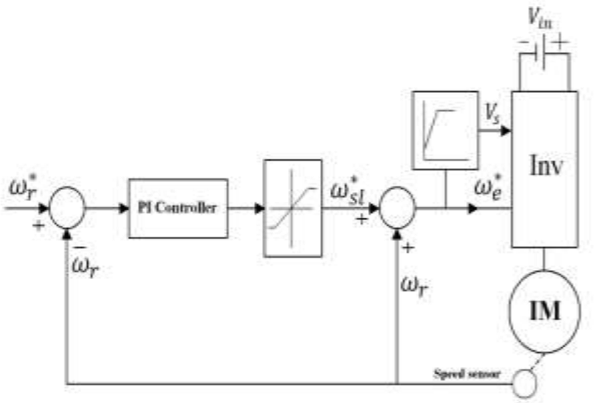

Fig:5. V/F based closed loop speed control scheme of an induction motor

Proportional-integral (PI) controller assisted with a feed forward d_0 is used as the shoot-through compensator. Capacitor voltage v_{C1} is measured and fed back. Laplace-transformed transfer functions of the Z-source network can be obtained via (5). The feed forward d_0 is determined according to the inherent relationship of v_{C1} and v_{in} in steady state:

$$d_0 = \frac{v_{C1}^* - v_{in}}{2v_{C1}^* - v_{in}} \quad (6)$$

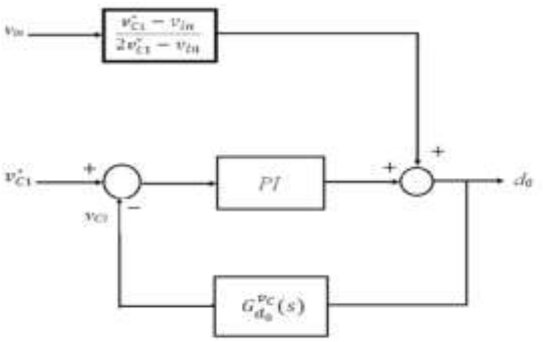

Fig. 6: DC voltage control block diagram of a ZSI

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In order to prevent the clashes between the dynamics of ac- and dc-sides, the dc-side dynamics should be made considerably slower. By doing so, the ac output can be regulated quickly with a relative stable dc voltage to avoid interactive oscillation between the dc and ac side. This could be supported by having a relatively lower bandwidth in the dc-side voltage loop. However, fast response of the dc-side controller is still necessary for good performance of the whole system. With the system specifications listed in [**Table- 1]**, bode plot of the dc-side controller can be obtained. As shown in **[Figure- 7]**, with k_p = 2e-4, k_i = 0.4, the crossover frequency is set to 32 Hz.

TABLE I: Z-source Inverter Parameters

Parameter	value	Unit
C	400	μF
L	500	μH
R	0.47	Ω
r	0.03	Ω
V_{in}	130	V
D_0	0.25	-
I_{load}	10	A

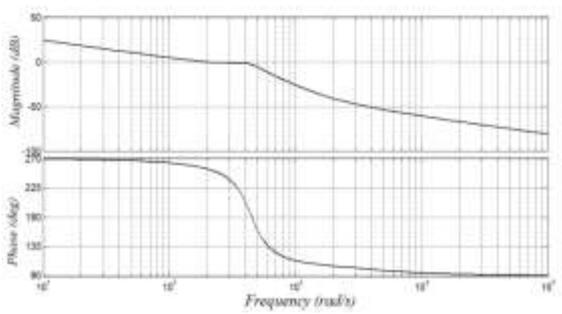

Fig:7. Frequency response of voltage loop gain

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MATERIALS AND METHODS

Simulation Results

The standard mode of operation of an ASD is to maintain the DC link voltage at a constant value and adjust the modulation index M to control the output voltage. As described in [2], the modulation index M plays an important role on the motor iron losses and the ripple current below base speed. As a consequence, in order to reduce the iron losses it is better to operate with the highest allowed modulation index.

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In order to verify the proposed closed loop speed control and peak dc-link voltage control strategies, several simulations are carried out using MATLAB/SIMULINK for a sample induction motor using the parameters in Table II. The specifications of Z-source network used in simulation are presented in Table III. In the simulation model, the constant boost PWM control method is used and the modulation index is calculated from the reference voltage in V/F control method.

In the proposed closed loop Z-source inverter ASD system, in order to make the inverter operate with higher modulation index, the dc link voltage is controlled to be constant by the closed loop shoot-through control. The modulation index is calculated by the V/F control with variable operating frequency.

TABLE 2. Induction Motor Parameters

Parameter	value	Unit
Output power	7	hp
RMS line voltage	400	V
Input frequency	60	Hz
Numbers of poles	4	-
Stator resistance, R_s	0.8	Ω
Rotor resistance, R_r'	0.6	Ω
Stator inductance, L_{ls}	5.974	mH
Rotor inductance, L_{lr}'	5.974	mH
Mutual inductance, L_m	20.37	mH
Inertia, J	0.02	$kg.m^2$
Fraction Factor, F	0.005752	N.m.s

TABLE: 3. Quasi Z-source network Parameters

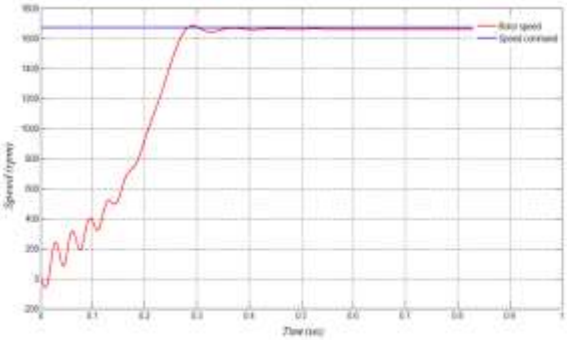
Parameter	alue	nit
Capacitor	400	μF
Inductance	500	μH
DC input voltage	513	V
AC output RMS line voltage	400	V
Switching frequency	10	kHz

RESULTS

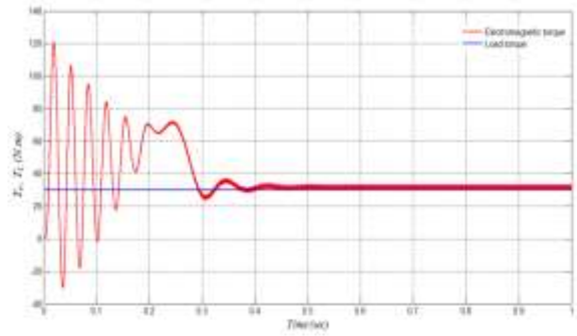
In order to investigate the ability of the proposed control system, the simulation was performed in two cases .At the first case, it is assumed the speed command is increased from 800 rpm to 1000 rpm. The simulation results in this case are shown in **[Figure- 9]**. At the second case, the load torque is increased from 10 N.m to 15 N.m**[Figure- 10]** shows the simulation results in this case.

The simulation results in both cases verify the validity of the proposed close loop control system.

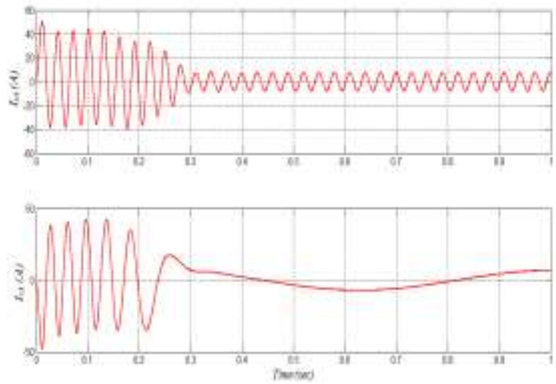
THE IIOAB JOURNAL
ISSN: 0976-3104



(a)



(b)



(c)

Fig. 8: System response during start up, a) motor speed, b) electromagnetic and load torque, c) stator and rotor current

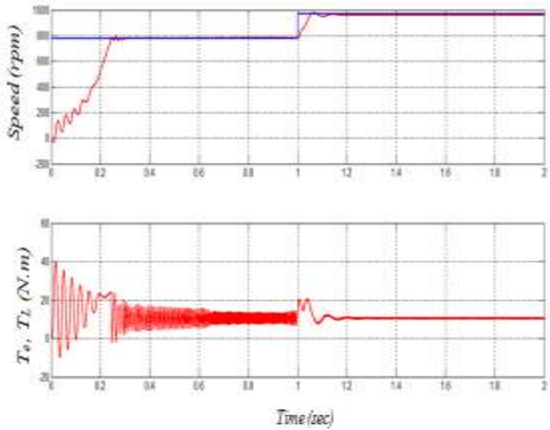


Fig. 9: System response during speed command increase

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ISSN: 0976-3104

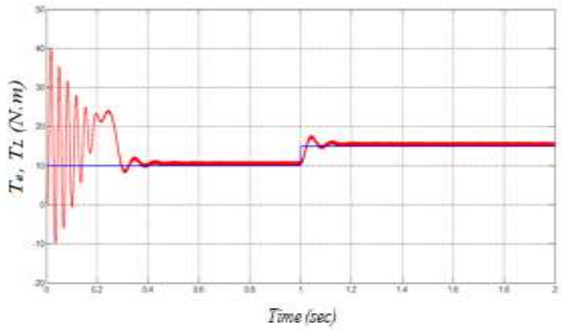

Fig. 10: System response during load torque increase

DISCUSSION

In this paper a new closed loop speed control of induction motor fed by Z-source inverter based on V/F control has been proposed. The unique features of ZSI cause the proposed system has many advantages compared with traditional speed control system fed by voltage source inverters. The dc link voltage is controlled by a proposed closed loop controller. The controller parameters of dc side has been determined by using the dynamic model of ZSI. The simulation results verified the ability of the proposed closed loop speed control system during start up, load disturbance and changing of speed command.

CONFLICT OF INTEREST

The author declares having no competing interests.

ACKNOWLEDGEMENT

None

FINANCIAL DISCLOSURE

None

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