

Indirect Vector Control of Multi Cage Induction Motor

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ABSTRACT

This paper presents a methodology for indirect vector control of a double cage induction motor. Vector control or field oriented control offers more precise control of high performance drives where oscillations in air gap flux linkages are intolerable. The mathematical model of a double cage induction machine is proposed. The developed model is studied with constant V/f control taking the boost voltage into account and indirect vector control. A comparison is made between the two control methods. Finally Simulation results have shown better results with indirect vector control compared to constant V/f control.

General Terms

Double-cage induction machine model, Indirect vector control, constant V/f control.

Keywords

Double cage induction motor, constant V/f control, Indirect vector control,.

1. INTRODUCTION

Induction machines with double cage rotor winding are commonly utilized in medium and high power applications. In applications that require high starting torque double-cage induction machine is preferred. Mathematical modeling approach for double-cage or deep-bar type induction machine is same. Representation of the rotor with two rotor windings rather than with a single winding is known to lead to significant improvement in the accuracy of simulation results for both deep-bar and double-cage induction machines[1]. The squirrel cage induction motor may be modeled with a double cage model in order to predict well starting current and torque [2]. The goal of this paper is to study the speed control of the squirrel-induction machine with a double cage model, by using constant V/f control strategy. A new approach i.e. indirect vector control with boost voltage is proposed. Finally comparative simulation results of double cage model of squirrel cage induction motor with constant volts/Hz and indirect vector control is discussed.

1.1 MODEL OF A DOUBLE CAGE INDUCTION MACHINE

The induction machine is often modeled with the single-cage model. However, this model is only acceptable for the wound rotor induction motors [2].

Single-cage type induction machines should be modeled with a double cage model. Deep, narrow rotor bars can be taken into account with this model because they have torque-speed characteristics similar to those of double-cage rotors. So that, single-cage rotor has been modeled, to take into account the skin effect which is very pronounced at starting conditions, with a double-cage model.

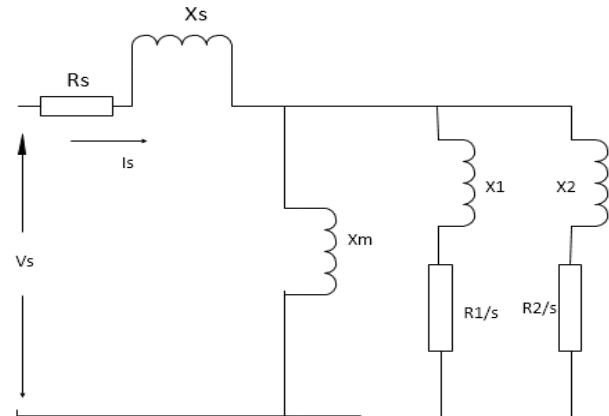


Fig 1: Equivalent circuit of double-cage induction motor

The mathematical model of a double-cage induction machine is arranged in a manner which is closely similar to the derivation of the (d,q) model of a single-cage induction machine. Due to the additional second cage, the rotor is now described with four differential equations in a reference frame fixed in a stator as shown in Figure 2. The symbols used through the paper are defined in the Nomenclature.

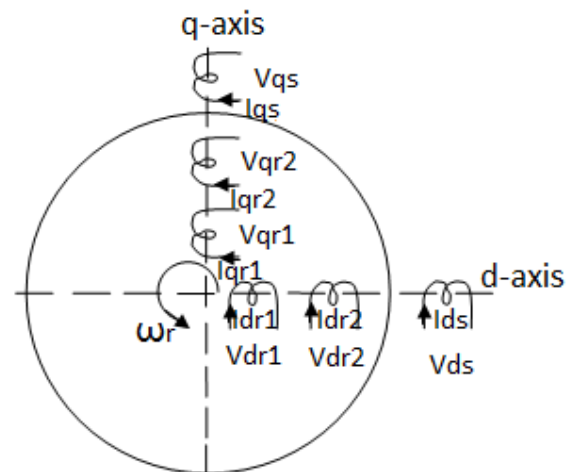


Fig 2: Double-cage model using park transformation in the fixed reference frame (d,q)

By adopting the well-known assumptions of the generalized theory of electrical machines, the double-cage induction motor can be described in a reference frame (d,q) with the following set of differential and algebraic equations [4].

$$V_{ds}^e = R_s i_{ds}^e + \frac{d\psi_{ds}^e}{dt} + \omega_e \psi_{qs}^e \quad (1)$$

$$V_{qs}^e = R_s i_{qs}^e + \frac{d\psi_{qs}^e}{dt} + \omega_e \psi_{ds}^e \quad (2)$$

$$V_{qr1}^e = R_{r1} i_{qr1}^e + \frac{d\psi_{qr1}^e}{dt} + (\omega_e - \omega_r) \psi_{dr1}^e \quad (3)$$

$$V_{dr1}^e = R_{r1} i_{dr1}^e + \frac{d\psi_{dr1}^e}{dt} + (\omega_e - \omega_r) \psi_{qr1}^e \quad (4)$$

$$V_{qr2}^e = R_{r2} i_{qr2}^e + \frac{d\psi_{qr2}^e}{dt} + (\omega_e - \omega_r) \psi_{dr2}^e \quad (5)$$

$$V_{dr2}^e = R_{r2} i_{dr2}^e + \frac{d\psi_{dr2}^e}{dt} + (\omega_e - \omega_r) \psi_{qr2}^e \quad (6)$$

The magnetizing flux linkage may then be written as

$$\psi_{ds}^e = L_{ls} i_{ds}^e + L_m (i_{ds}^e + i_{dr1}^e + i_{dr2}^e) \quad (7)$$

$$\psi_{qs}^e = L_{ls} i_{qs}^e + L_m (i_{qs}^e + i_{qr1}^e + i_{qr2}^e) \quad (8)$$

$$\psi_{qr1}^e = L_{lr1} i_{qr1}^e + L_m (i_{qs}^e + i_{qr1}^e + i_{qr2}^e) \quad (9)$$

$$\psi_{qr2}^e = L_{lr2} i_{qr2}^e + L_m (i_{qs}^e + i_{qr1}^e + i_{qr2}^e) \quad (10)$$

$$\psi_{dr2}^e = L_{lr2} i_{dr2}^e + L_m (i_{qs}^e + i_{dr1}^e + i_{dr2}^e) \quad (11)$$

$$\psi_{dr1}^e = L_{lr1} i_{dr1}^e + L_m (i_{ds}^e + i_{dr1}^e + i_{dr2}^e) \quad (12)$$

$$\psi_{dm}^e = L_m (i_{ds}^e + i_{dr1}^e + i_{dr2}^e) \quad (13)$$

$$\psi_{qm}^e = L_m (i_{qs}^e + i_{qr1}^e + i_{qr2}^e) \quad (14)$$

Mutual flux linkage between the stator and inner cage is L_{m1} and between stator and outer cage is L_{m2} . Again between outer cage and inner cage is L_{m12} . L_{m12} is slightly higher than L_{m1} and L_{m2} but with approximation $L_{m1} = L_{m2} = L_{m12}$. The electromagnetic torque expression can be written as

$$T_e = \left(\frac{3}{2} \right) \left(\frac{p}{2} \right) (\psi_{ds}^e i_{qs}^e - \psi_{qs}^e i_{ds}^e) \quad (15)$$

Or,

$$T_e = \left(\frac{3}{2} \right) \left(\frac{p}{2} \right) L_m \left[(i_{dr1}^e i_{qs}^e - i_{qr1}^e i_{ds}^e) + (i_{dr2}^e i_{qs}^e - i_{qr2}^e i_{ds}^e) \right] \quad (16)$$

Where,

$$\omega_m = \left(\frac{2}{p} \right) \omega_r \quad (17)$$

2. PRINCIPLE AND STRATEGY OF THE INDIRECT VECTOR CONTROL

In case of induction machines, the control is usually performed in the reference frame (d-q) attached to the rotor flux space vector. That's why the implementation of vector

control requires information on the modulus and the space angle (position) of the rotor flux space vector. The stator currents of the induction machine are separated into flux- and torque-producing components by utilizing transformation to the d-q coordinate system, whose direct axis (d) is aligned with the rotor flux space vector. That means that the q-axis component of the rotor flux space vector is always zero.

The slip difference between the rotor speed and the synchronous speed is given by

$$\omega_{sl} = \omega_e - \omega_r \quad (18)$$

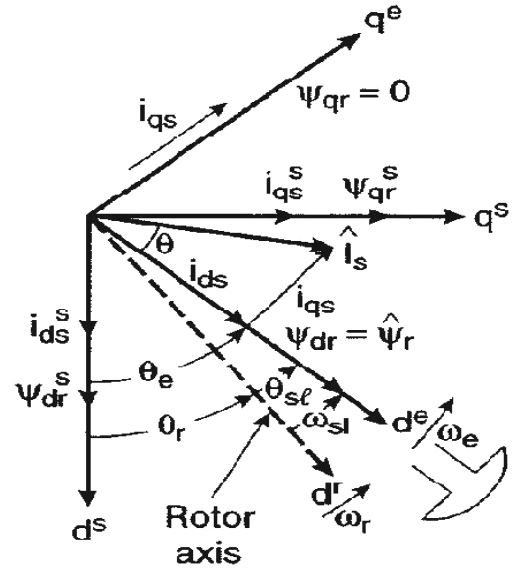


Fig 3: Indirect vector control phasor diagram

In order to ensure decoupling between the stator flux and the torque, the torque component of the current, i_{qs}^e , should be aligned with the q^e axis and the stator flux component of current, i_{ds}^e , should be aligned with the d^e axis as shown in Figure 3.

The rotor circuit equations may be written as

$$\frac{d\psi_{dr1}^e}{dt} + R_{r1} i_{dr1}^e - \omega_{sl} \psi_{qr1}^e = 0 \quad (20)$$

$$\frac{d\psi_{qr1}^e}{dt} + R_{r1} i_{qr1}^e + \omega_{sl} \psi_{dr1}^e = 0 \quad (21)$$

$$\frac{d\psi_{dr2}^e}{dt} + R_{r2} i_{dr2}^e - \omega_{sl} \psi_{qr2}^e = 0 \quad (22)$$

$$\frac{d\psi_{qr2}^e}{dt} + R_{r2} i_{qr2}^e + \omega_{sl} \psi_{dr2}^e = 0 \quad (23)$$

For decoupling control the total rotor flux ψ_r^{e*} needs to be aligned with the d^e -axis i.e

$$\psi_r^{e*} = \psi_{dr}^e = \psi_{dr1}^e + \psi_{dr2}^e \quad (24)$$

$$\text{And } \psi_{qr}^e = \psi_{qr1}^e + \psi_{qr2}^e = 0$$

So $\psi_{qr1}^e = 0$ and $\psi_{qr2}^e = 0$

Now with constant rotor flux the rotor circuit equation can be rewritten as

$$i_{dr1}^e = 0 \quad (25)$$

$$R_{r1}i_{qr1}^e + \omega_{sl}\psi_{dr1}^e = 0 \quad (26)$$

$$i_{dr2}^e = 0 \quad (27)$$

$$R_{r2}i_{qr2}^e + \omega_{sl}\psi_{dr2}^e = 0 \quad (28)$$

Adding the above equations

$$\omega_{sl}\psi_r^{e*} = -\left(r_{r1}i_{qr1}^e + r_{r2}i_{qr2}^e\right) \quad (29)$$

The rotor currents may be written from the magnetizing flux linkage as

$$i_{qr1}^e = \frac{i_{qs}^e (L_m^2 - L_m L_{r2})}{L_{r1} L_{r2} - L_m^2} \quad (30)$$

$$i_{qr2}^e = \frac{i_{qs}^e (L_m^2 - L_m L_{r1})}{L_{r1} L_{r2} - L_m^2} \quad (31)$$

Now substituting the above values

$$\omega_{sl}^* = \frac{L_m i_{qs}^* \left[(L_{r2} - L_m) r_{r1} + (L_{r1} - L_m) r_{r2} \right]}{(L_{r1} L_{r2} - L_m^2) \psi_r^*} \quad (32)$$

After simplification, electromagnetic torque is

$$T_e^* = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)\left(\frac{L_m}{2}\right)\left(\frac{L_{r1}L_{r2} - L_m^2}{L_{r1} + L_{r2} - 2L_m}\right)\psi_r^{e*}i_{qs}^{e*} \quad (33)$$

$$\text{So } i_{qs}^{e*} = \left(\frac{T_e^*}{\psi_r^{e*}} \right) \left(\frac{8}{3pL_m} \right) \left(\frac{L_{r1} + L_{r2} - 2L_m}{L_{r1}L_{r2} - L_m^2} \right) \quad (34)$$

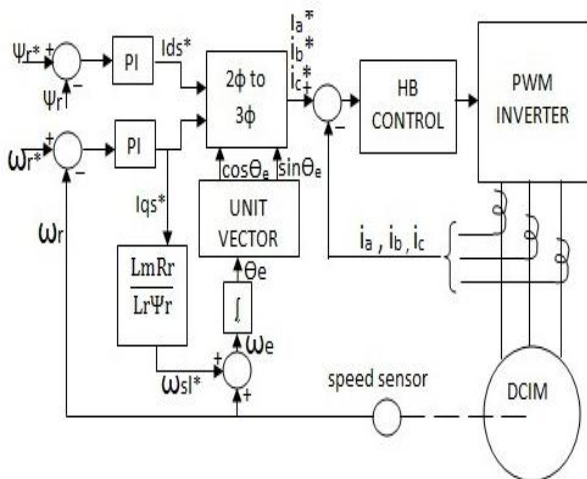


Fig 4: Scheme of indirect vector control method

3. PRINCIPLE AND STRATEGY OF THE CONSTANT V/f CONTROL

The principle of constant V/f control requires that, the magnitude and frequency of the voltage applied to the stator of a motor maintain a constant ratio. By this scheme, the magnitude of the magnetic field in the stator is kept at an

approximately constant level throughout the operating range. Thus, maximum constant torque producing capability is maintained. However, when the frequency and hence also the voltage are low, the voltage drop across the stator resistance cannot be neglected and must be compensated with boost voltage. At frequencies higher than the rated value, the constant V/Hz principle also have to be violated because, to avoid insulation break down, the stator voltage must not exceed its rated value.

The actual rotor speed is compared with its reference value ω_m^* and the error is processed through a PI controller with a limiter to obtain the slip speed command ω_{sl}^* (within the maximum allowable slip speed of the induction motor).

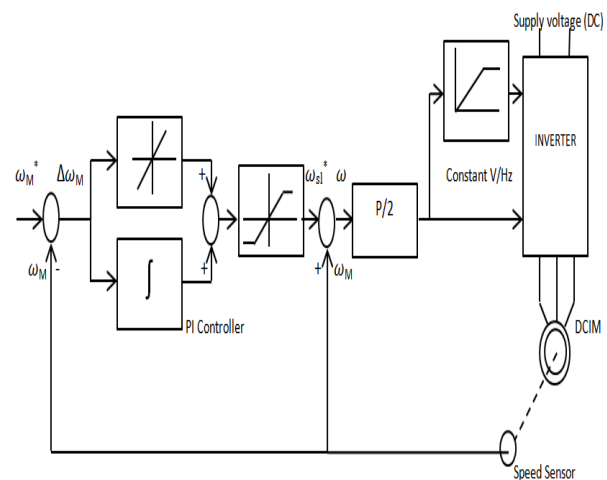


Fig 5:Block-diagram of a V/f Speed Control Loop System

The slip speed command is added to rotor speed to obtain the stator frequency command. Thereafter a Boost voltage is added to the voltage, proportional to stator frequency and the result is processed through a sinusoidal modulator and PWM firing scheme to generate gate pulses that is required for inverter fed induction motor drive.

The expression for maximum torque from the equivalent circuit is

$$T_{\max} = \left(\frac{3P}{4\omega_e} \right) \left(\frac{V_s^2}{R_s + \sqrt{R_s^2 + (X_s + X_r')^2}} \right) V_1 \quad (35)$$

Again

$$T_{\max} = \left(\frac{3P}{4\omega_e} \right) \left(\frac{K \left(\frac{V_s}{f} \right)^2}{\frac{R_s}{f} + \sqrt{\left(\frac{R_s}{f} \right)^2 + 4\Pi^2 (L_s + L_r)^2}} \right) \quad (36)$$

Where X_r' = Equivalent rotor reactance and L_r' = Equivalent rotor inductance. Determination of boost voltage includes

* T_{\max} is calculated from the Torque-speed characteristic.

*At a particular frequency, the supply voltage required V_1 is calculated by using constant V_s / f ratio and the actual voltage V_2 required for T_{\max} is calculated by using above equation.

*The boost voltage at a particular frequency is calculated by taking the difference between the V_2 and V_1 .

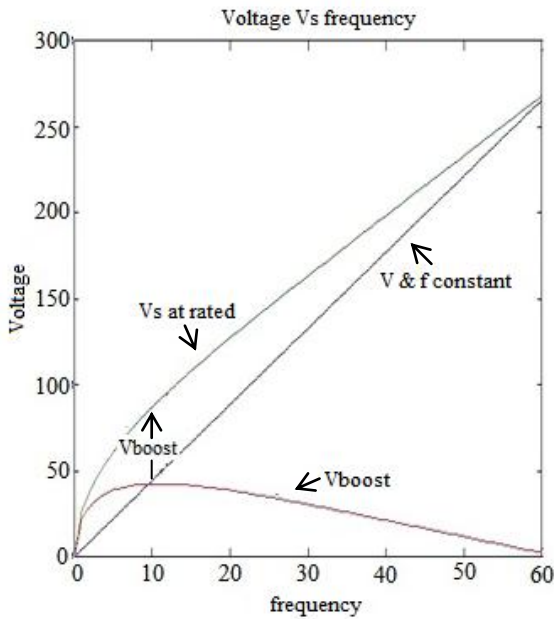


Fig 6: Vboost lookup table programming result

The above result shows the variation of boost voltage with respect to frequency to retain the same maximum torque at low speeds. So v/f ratio is maintained constant below the base speed, except at low frequencies where v/f ratio is increased by adding the boost voltage to keep maximum torque constant.

4. SIMULATION RESULTS AND ANALYSIS

Simulations were carried out using the software Matlab/Simulink. The mathematical model of the double-cage induction machine, used in this simulation, is given in section II. The motor under investigation is 11Kw, 400-volt, 50Hz, 4 poles, three phase double squirrel-cage induction motor. The machine parameters are given in the appendix.

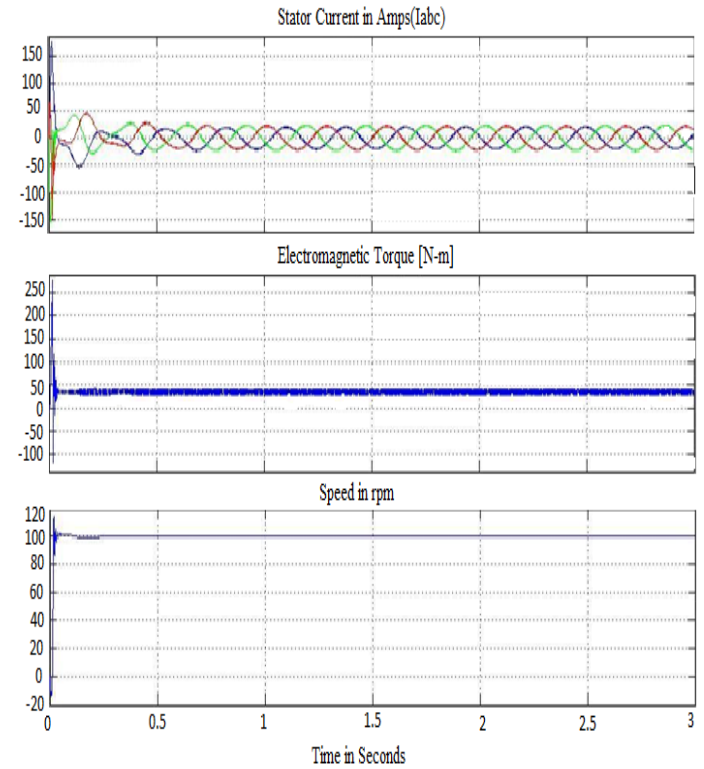


Fig 7: $N_r^* = 100\text{rpm}$ with 50% full load torque (v/f control with lookup table vboost)

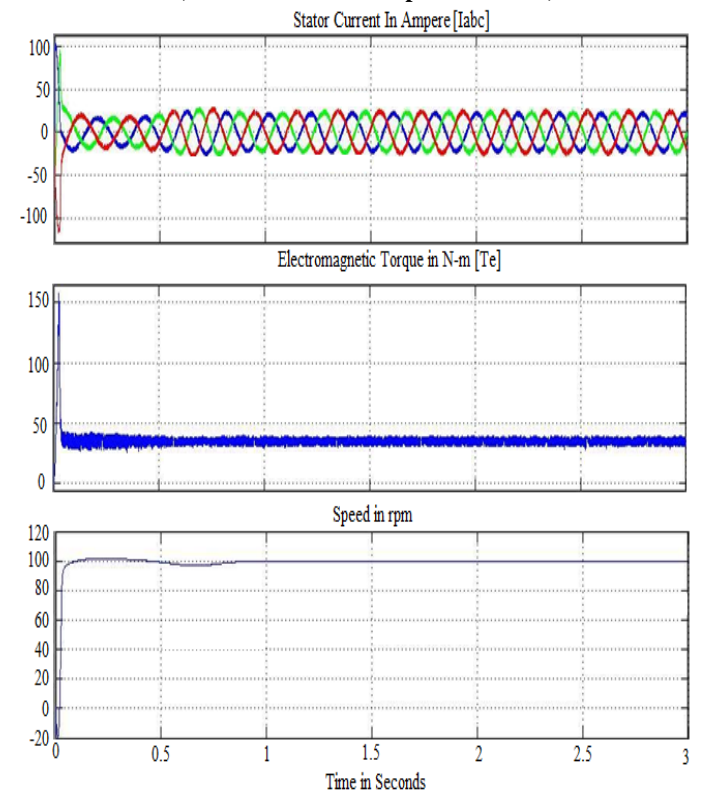


Fig 8: $N_r^* = 100\text{rpm}$ with 50% full load torque (Indirect vector control)

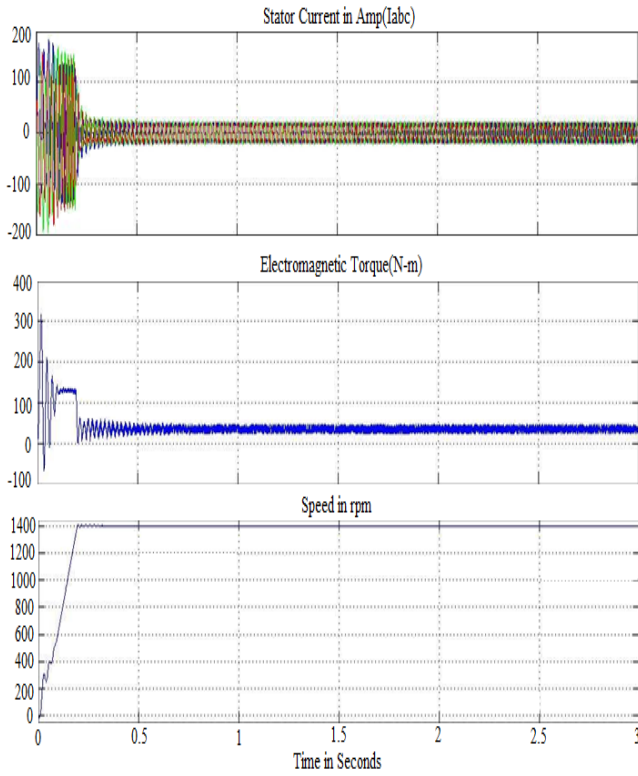


Fig 9: $N_r^* = 1400\text{rpm}$ with 50% full load torque (v/f control with lookup table vboost)

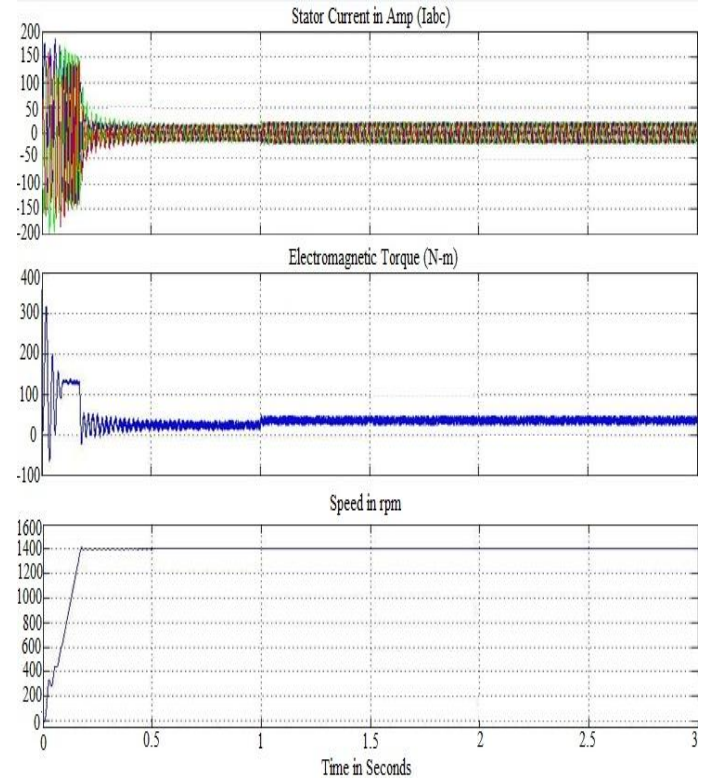


Fig 11: $N_r^* = 1400\text{rpm}$ with T_L varied from 33% to 50% full load torque (v/f control with lookup table vboost)

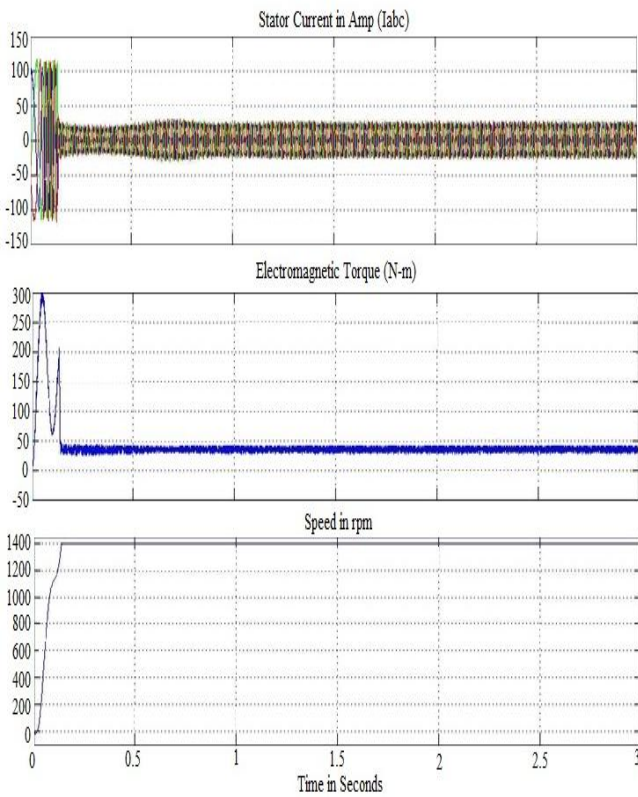


Fig 10: $N_r^* = 1400\text{rpm}$ with 50% full load torque (indirect vector control)

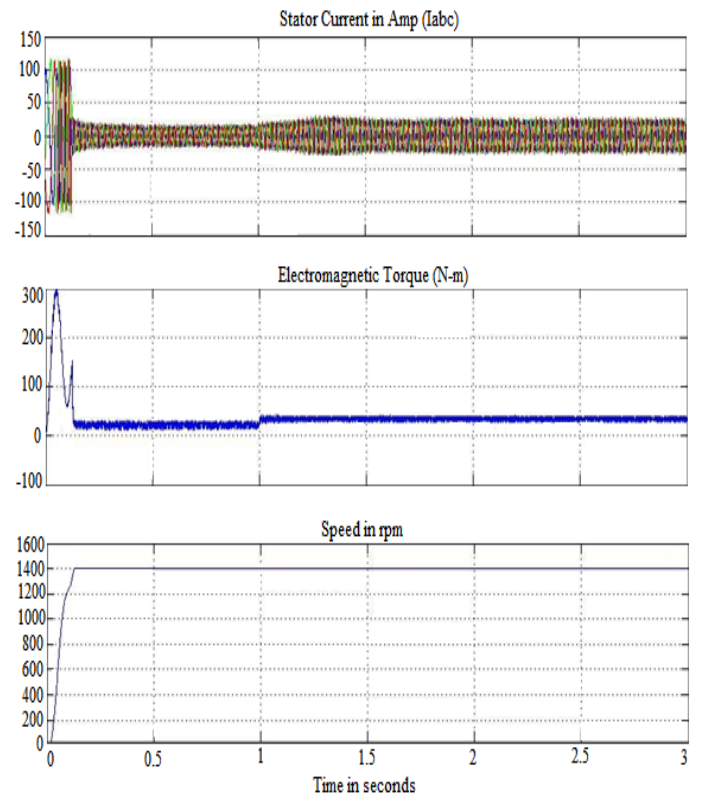


Fig 12: $N_r^* = 1400\text{rpm}$ with T_L varied from 33% to 50% full load torque (indirect vector control)

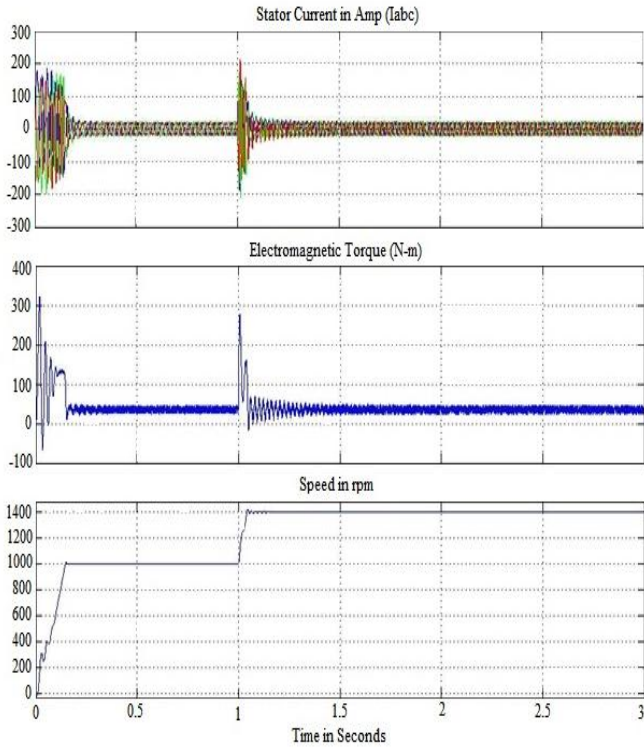


Fig 13: N_r^* varied from 1000 rpm to 1400rpm with 50% full load torque (v/f control with lookup table vboost)

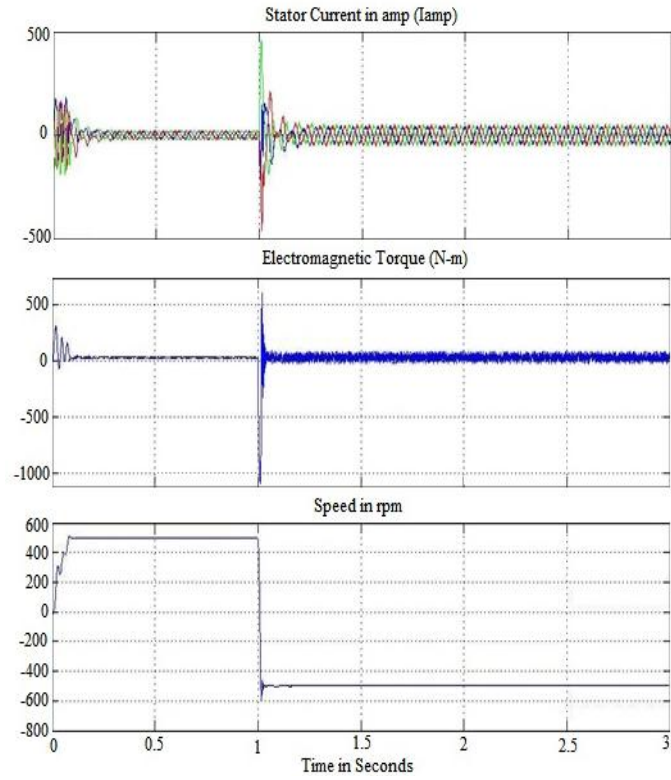


Fig 15: N_r^* varied from 500 rpm to -500 rpm with 50% full load torque (v/f control with lookup table vboost)

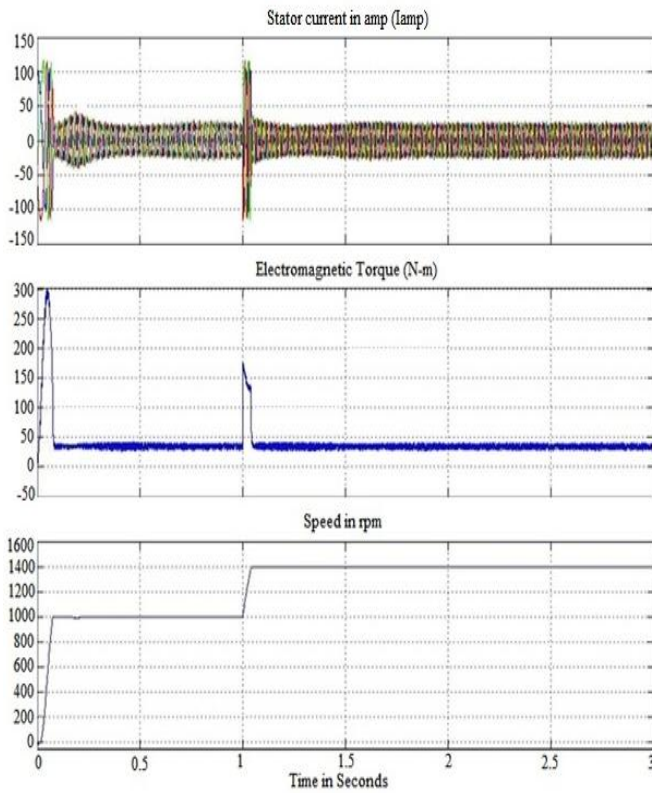


Fig 14: N_r^* varied from 1000 rpm to 1400rpm with 50% full load torque (indirect vector control)

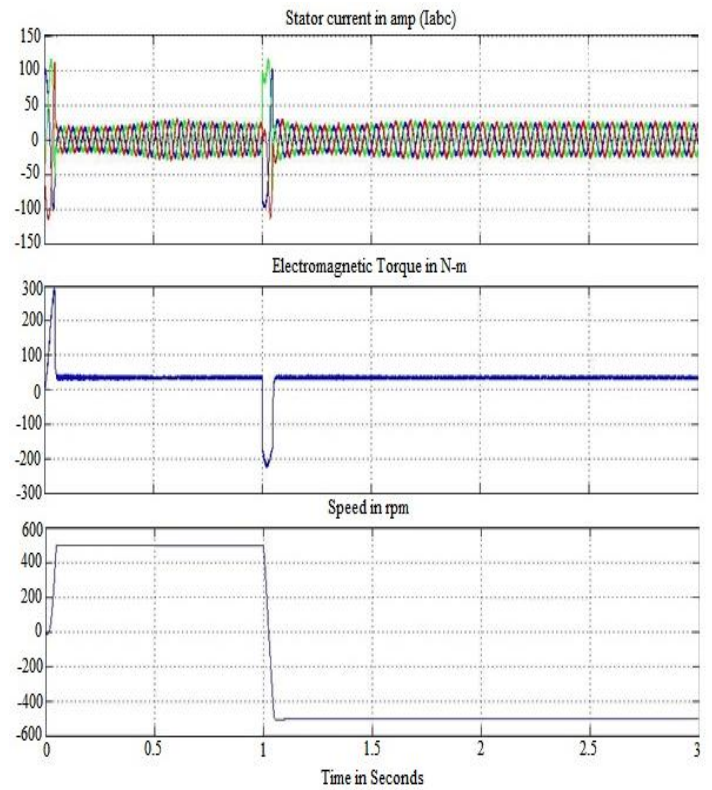


Fig 16: N_r^* varied from 500 rpm to -500rpm with 50% full load torque (indirect vector control)

5.1 Constant V/f control with Vboost

The corresponding simulation results, of the constant V/f control with Vboost of double squirrel-cage induction motor, are shown in Figure 7, Figure 9, Figure 11, Figure 13 and Figure 15, where the curves for the speed, electromagnetic torque and stator currents are given.

5.2 Indirect vector control

The corresponding simulation results, of the indirect vector control of double squirrel-cage induction motor, are shown in Figure 8, Figure 10, Figure 12, Figure 14 and Figure 16, where the curves for the speed, electromagnetic torque and stator currents are given.

Table 1. Comparative results for speed of 100 and 1400

Speed in rpm		100	1400
Constant V/f control	T_s in Nm	270	315
	I_s in Amp.	170	170
	Torque pulsation in Nm.	10	22
	I_{ss} in Amp.	22	22
	t_{ss} in sec.	0.235	0.38
Indirect Vector control	T_s in Nm	150	300
	I_s in Amp.	95	116
	Torque pulsation in Nm.	9	12
	I_{ss} in Amp.	25	25
	t_{ss} in sec.	0.85	0.14

Table 2. Comparative results for varying speed

Speed in rpm		1000 To 1400	500 To -500
Constant V/f control	T_s in Nm	270	-600
	I_s in Amp.	170	450
	Torque pulsation in Nm.	24	100
	I_{ss} in Amp.	22	20 to 45
	t_{ss} in sec.	0.17	0.16
Indirect Vector control	T_s in Nm	175	-220
	I_s in Amp.	115	110
	Torque pulsation in Nm.	12	10
	I_{ss} in Amp.	25	22
	t_{ss} in sec.	0.042	0.055

Table 3. Comparative results for electromagnetic Torque

Speed in RPM	1400		
T_L in Nm. 33% to 50% of Full Load Torque	Constant V/f control	Torque pulsation in Nm.	25
		I_{ss} in Amp.	22
		t_{ss} in sec	0.05
	Indirect Vector control	Torque pulsation in Nm.	12
		I_{ss} in Amp.	25
		t_{ss} in sec	0.05

Table 4. Performance analysis

Speed in rpm	Power factor	
	v/f speed control with lookup table Vboost	Indirect vector control
1400	0.765	0.89
1200	0.76	0.887
1000	0.754	0.885
800	0.74	0.88
600	0.72	0.85
400	0.685	0.82
200	0.57	0.74
100	0.43	0.68

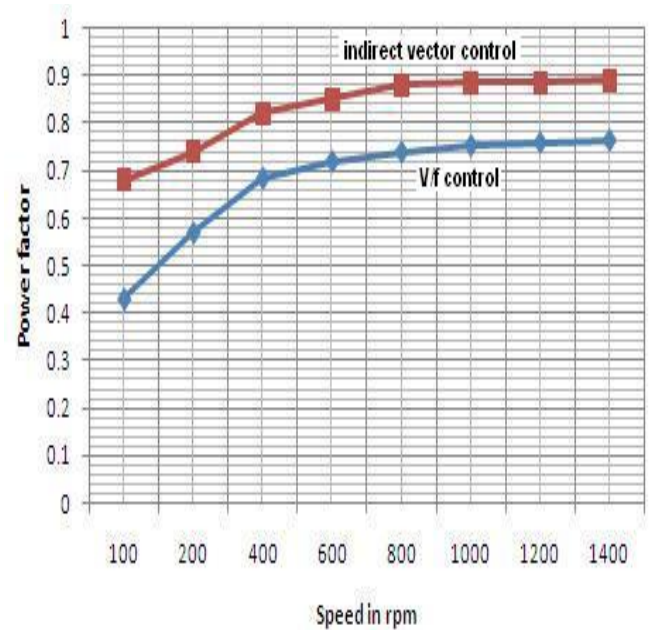


Fig 17: Graphical analysis of power factor vs speed

5. CONCLUSION

The simulation results show the excellent response achieved with the indirect vector control method as compared to constant v/f control method even at extremely low frequency in terms of low torque pulsation, less stator current ripple and lower steady state time. Simulation results validate the effectiveness of the proposed indirect vector control method during speed reversal operation over constant v/f control method that suffers from high transient instability. The performance analysis of induction motor has shown that indirect vector control method has a good dynamic behavior with improved power factor over the whole frequency range.

APPENDIX-MOTOR DATA

11Kw, 400V, 1480 rpm, $R_s=0.2113\Omega$, $X_{Ls}=0.7913\Omega$, $R_1=0.4226\Omega$, $X_{Lr1}=1.7004\Omega$, $R_2=1.6598\Omega$, $X_{Lr2}=0.7913\Omega$, $X_m=X_{l2}=26.096\Omega$, $J=0.11\text{kg.m}^2$, $P=4$.

NOMENCLATURE

V_s : Stator voltage per phase (V).
 V_{ds}^e : d-axis stator voltage (V).
 V_{qs}^e : q-axis stator voltage (V).
 V_{r2} : Rotor outer voltage per phase (V).
 R_s : Stator resistance.
 R_1 : Inner-cage rotor resistance.
 R_2 : Outer-cage rotor resistance.
 L_s : Stator cyclic inductance (H).
 L_{Lr1} : Rotor inner leakage inductance (H).
 L : Rotor outer Leakage inductance (H).
 L_{12} : Mutual inductance between two rotor cages (H).
 L_m : Magnetizing inductance (H).
 P : Number of poles.
 TL : Electromagnetic torque and load torque (Nm).

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