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High Performance Control Schemes of Induction Motor – A Review

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ABSTRACT: Induction motors are used in most of the industrial applications due to its reliability, robustness, low cost and low maintenance. The main focus of this paper is investigation of high performance control methods which are being applied to make induction motor with good dynamic behaviour. The high performance control methods investigated are vector control and direct torque control. The dynamic behaviour of induction motor is studied for step change in speed and step change in load. The results of Matlab/Simulink simulations of both methods are presented. The relative advantages and disadvantages of each method were highlighted.

Keywords: Induction motor, variable speed, electrical drives, vector control, direct torque control

I. INTRODUCTION

AC motors are classified into two major types, synchronous and asynchronous or induction motors. Induction motors have been widely used in industrial applications due to the reliability, robustness low cost and greatly reduced maintenance compared to other motors. Electrical motors take more than 50 percent of the total electrical power in the industries. In this more than 65 percent of the power is used by induction motor drives [1]. Even the principle of induction motor being known for more than 100 years, still a considerable progress is being achieved [2]. This is due to the advances in materials, power electronics and high speed digital controllers[1-2]. High performance motor applications require a fast torque response. Generally DC motors were preferred. Previously, torque response control was a problem in induction motors. The advancements in power electronic devices and high speed controllers provide the fast torque response control of induction motors [3, 9]. These controllers provide good steady state performance and transient behaviour [3].

The control methods of induction motor can be divided into two types as scalar control method and vector control method. In scalar control method magnitude and frequency are controlled. It is a simple method to implement. But due to the coupling effect it gives poor torque response. Vector control method has been proposed in early 1970s. It is also known as field oriented control. In this method, both magnitude and phase alignment of vector variables are considered. It provides fast torque response. In vector control, motor equations are transformed into field coordinates which is corresponding to the decoupled torque production in separately excited DC motor [4]. In mid of 1980s an advanced scalar control method known as direct torque control was introduced. Direct torque control method utilised the vector relationships, but replaces the coordinate transformation concept of vector control method. It also provides the fast torque response [5].

In this paper, the vector control or field oriented control and direct torque control methods are investigated. A brief overview of the operation of each method and the Matlab-Simulink simulation results are presented. A comparison of the two methods is included.

II. DYNAMIC MODEL OF INDUCTION MOTOR

The dynamic model of three phase induction motor can be written with the variables referred to the d-q synchronously rotating reference frame [5]. The dynamic d-q equivalent circuit of induction motor in synchronously rotating reference frame is given in Fig 1.

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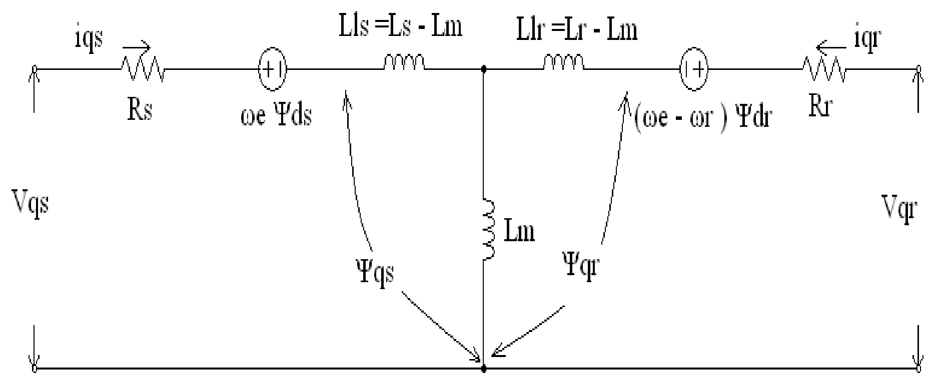
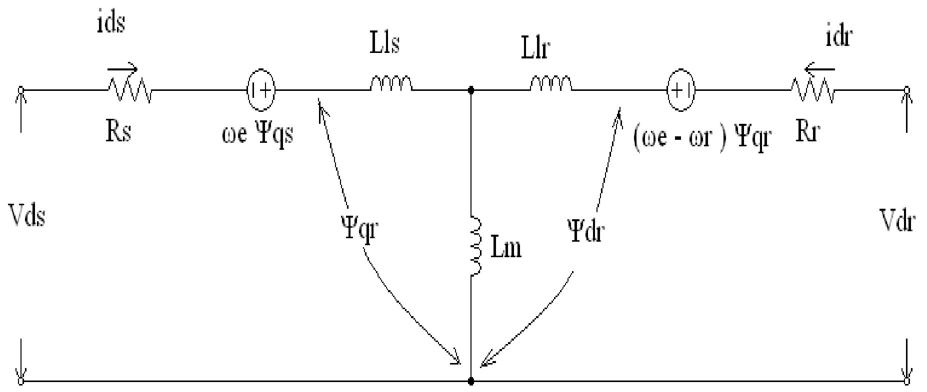


(a)



(b)

Fig 1. Dynamic Equivalent circuit in synchronously rotating reference frame.
(a). q-axis Circuit and (b). d-axis circuit

The stator circuit voltage equations are,

$$v_{qs} = R_s i_{qs} + \frac{d}{dt}\Psi_{qs} + \omega_e \Psi_{ds} \quad (1)$$

$$v_{ds} = R_s i_{ds} + \frac{d}{dt}\Psi_{ds} - \omega_e \Psi_{qs} \quad (2)$$

The rotor circuit voltage equations are,

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\Psi_{qr} + (\omega_e - \omega_r)\Psi_{dr} \quad (3)$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\Psi_{dr} - (\omega_e - \omega_r)\Psi_{qr} \quad (4)$$

Where, v_{qs} , v_{ds} are q and d axis stator voltages, v_{qr} , v_{dr} are q and d axis rotor voltages. i_{qs} , i_{ds} are q and d axis stator currents, i_{qr} , i_{dr} are q and d axis rotor currents. Ψ_{qs} , Ψ_{ds} are q and d axis stator flux linkages, Ψ_{qr} , Ψ_{dr} are q and d axis rotor flux linkages. R_s, R_r are stator and rotor resistances.

In the above equations, when $\omega_e = 0$ the equations revert to stationary reference frame. The advantage of synchronously rotating frame model is that all sinusoidal variables in stationary frame appear as dc quantities in synchronously rotating frame.

The stator flux linkage equations are,

$$\Psi_{qs} = L_{ls} i_{qs} + L_m(i_{qs} + i_{qr}) \quad (5)$$

$$\Psi_{ds} = L_{ls} i_{ds} + L_m(i_{ds} + i_{dr}) \quad (6)$$

The rotor flux linkage equations are,

$$\Psi_{qr} = L_{lr} i_{qr} + L_m(i_{qs} + i_{qr}) \quad (7)$$

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$$\Psi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) \quad (8)$$

Where, L_{ls}, L_{lr} are stator and rotor leakage inductance and L_m is the magnetising inductance.
The torque developed by the interaction of air gap flux and rotor mmf in vector form,

$$T_e = \frac{3}{2}\frac{P}{2}\bar{\Psi}_m \times \bar{I}_r \quad (9)$$

The developed torque in terms of d –q components,

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\Psi_{dr} i_{qs} - \Psi_{qr} i_{ds}) \quad (10)$$

Where, P is no. of poles, Ψ_m is air gap flux linkage and I_r is rms rotor current.

III. Indirect Field Oriented Control

The vector control or field oriented control consists of controlling stator currents [6], [8]. This control is based on transforming three phase time dependent variable into two phase time invariant system. This leads DC motor-like control to induction motor. Field oriented control requires two constant inputs, torque component and flux component. In synchronously rotating reference frame, i_{qs} and i_{ds} are analogous to torque and flux components. The stator currents are controlled in such manner that i_{qs} delivers the desired torque while i_{ds} maintains the rotor flux. Speed error is used to generate desired torque. The phasor diagram of vector control is shown in Fig 2.

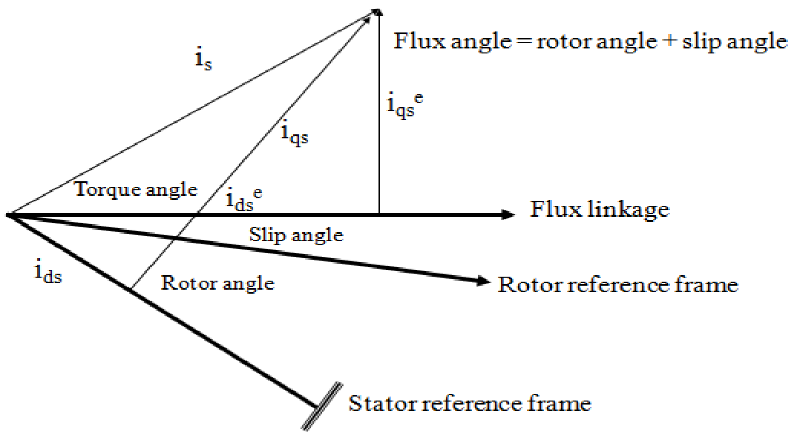

Fig 2. Phasor diagram of vector control

Indirect vector control is same as direct vector control except the unit vectors are generated in feed forward manner. Indirect vector control method is used in more number of industrial applications.

For singly fed squirrel cage inductor motor $v_{qr} = v_{dr} = 0$.

Rotor circuit equations (3) and (4) can be written as,

$$\frac{d}{dt}\Psi_{qr} + R_r i_{qr} + (\omega_e - \omega_r)\Psi_{dr} = 0 \quad (11)$$

$$\frac{d}{dt}\Psi_{dr} + R_r i_{dr} - (\omega_e - \omega_r)\Psi_{qr} = 0 \quad (12)$$

From Fig.3, for decoupling control, the stator flux component of current i_{ds} should be aligned on d^e - axis and the torque component of current i_{qs} should aligned on the q^e - axis.

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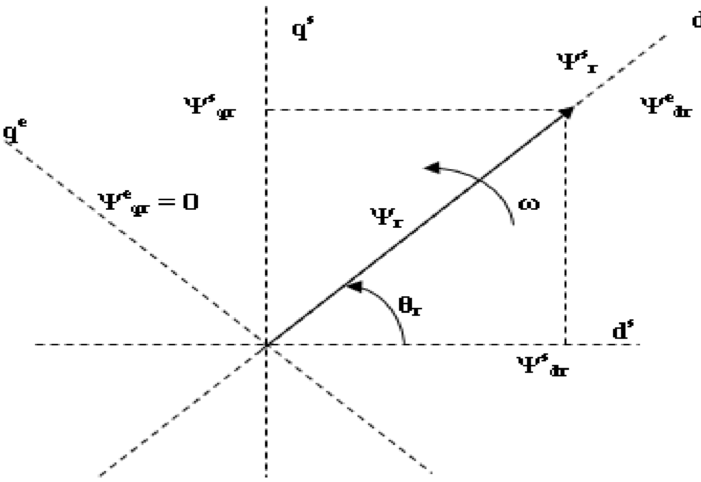

Fig 3. Orientation of the synchronously rotating reference frame along the rotor flux vector

For decoupling control,

$$\Psi_{qr} = 0 \quad (13)$$

and

$$\frac{d}{dt}\Psi_{qr} = 0 \quad (14)$$

The total rotor flux is on d^e – axis. The developed torque is now controlled by q^e – axis stator current i_{qs} only. The expression for developed torque from equation (10) becomes,

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\Psi_{dr} i_{qs} \quad (15)$$

If the flux is established and kept it constant, the torque response depends on quadrature axis stator current only. It can be fast and well controlled.

The block diagram of indirect field oriented control of induction motor is shown in Fig 4. In this indirect vector control the rotor current is controlled from the information of stator current and the rotor speed [10]. The instantaneous stator currents i_a, i_b, i_c and the rotor speed ω_r are measured. Then i_a, i_b and i_c converted to synchronously rotating reference frame direct axis current i_d and quadrature axis current i_q. The instantaneous stator currents i_a, i_b, and i_c are first transformed to stationary axis direct axis current i_{ds}^s and quadrature axis current i_{qs}^s using clark transformation.

$$i_{qs}^s = i_a \quad (16)$$

$$i_{ds}^s = \frac{i_a + 2i_b}{\sqrt{3}} \quad (17)$$

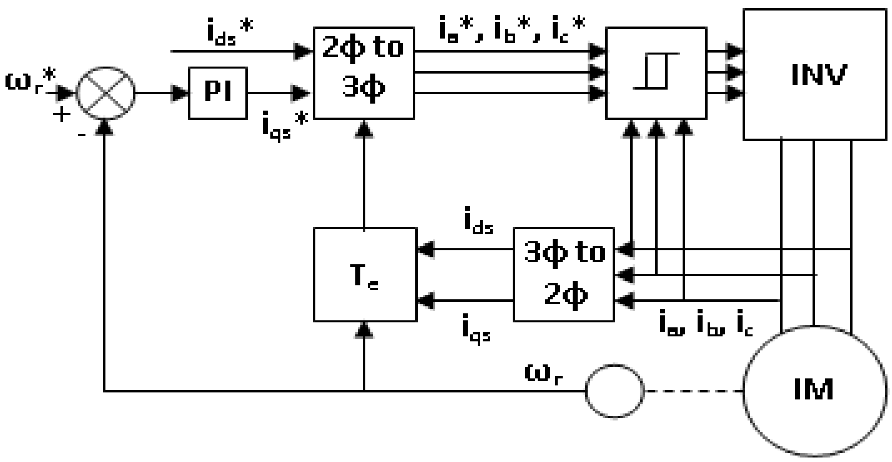

Fig 4. Indirect field oriented control

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The stationary frame stator currents i_{ds}^{s} and i_{qs}^{s} are transformed tor synchronously rotating reference frame stator currents i_{ds} and i_{qs} using park transformation. The unit vectors are calculated from rotor flux.

$$i_{qs} = i_{qs}^{s}\cos\theta_e - i_{ds}^{s}\sin\theta_e \quad (18)$$

$$i_{ds} = i_{qs}^{s}\sin\theta_e + i_{ds}^{s}\cos\theta_e \quad (19)$$

The stator currents i_{ds} and i_{qs} represented as DC quantities and it can be controlled independently using the controllers. The speed error is processed through the PI controller. The flux error and the torque error are computed and then it is converted to reference stator currents i_a*, i_b*and i_c*.

The synchronously rotating reference frame stator currents i_{ds} and i_{qs} are transferred to stationary axis stator currents using inverse park transform.

$$i_{qs}^{s} = i_{ds}\sin\theta_e + i_{qs}\cos\theta_e \quad (20)$$

$$i_{ds}^{s} = i_{ds}\cos\theta_e - i_{qs}\sin\theta_e \quad (21)$$

Then it is transferred to reference stator currents i_a*, i_b*and i_c* using inverse clark transformation.

$$i_a^* = i_{qs}^{s} \quad (22)$$

$$i_b^* = \frac{i_{qs}^{s}+\sqrt{3}i_{ds}^{s}}{2} \quad (23)$$

$$i_c^* = \frac{i_{qs}^{s}+\sqrt{3}i_{ds}^{s}}{2} \quad (24)$$

The reference stator currents and actual stator currents are given to hysteresis controller. The hysteresis controller generates the control signals to the three phase voltage source inverter [12]. It controls the induction motor.

IV. DIRECT TORQUE CONTROL

Direct torque control method is based on control of torque and flux to desired magnitude by selection of the appropriate voltage vector according to the predefined switching table [7].

In vector form the developed torque is expressed as,

$$\bar{T}_e = \frac{3}{2}\frac{P}{2}\bar{\Psi}_s \times \bar{I}_s \quad (25)$$

The magnitude of developed torque can be and expressed in terms of stator and rotor fluxes as,

$$\bar{T}_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r L_s'}|\bar{\Psi}_r||\bar{\Psi}_s|\sin\gamma \quad (26)$$

Where, $L_s' = L_s L_r - L_m^2$ and γ is the angle between the fluxes.

Generally the rotor time constant is larger than stator time constant. The rotor flux changes slowly compared to stator flux. The developed torque can be varied, if the rotor flux remains constant and stator flux and the angle γ is varied.

The rate of change of stator flux is given as

$$\frac{d\bar{\Psi}_s}{dt} = \bar{V}_s - R_s\bar{I}_s \quad (27)$$

If the ohmic drop is neglected,

$$\frac{d\bar{\Psi}_s}{dt} = \bar{V}_s \quad (28)$$

or

$$\Delta\bar{\Psi}_s = \bar{V}_s\,\Delta t \quad (29)$$

The stator flux can be varied by varying stator voltage vector for time increment. It is shown in Fig 5.

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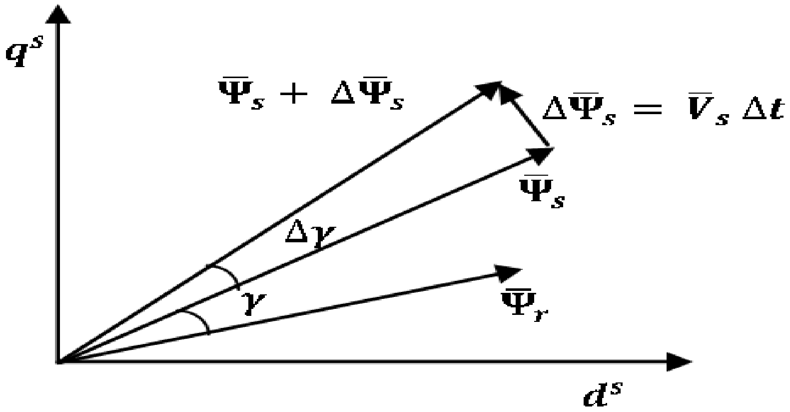

Fig 5. Stator and rotor flux vectors

The block diagram of the direct torque control of induction motor is in Fig 6. The desired value of flux Ψ_s^* and torque T_e^* are computed from desired speed ω_r^* and actual speed ω_r. The desired flux Ψ_s^* is compared with actual flux Ψ_s to generate flux error E_Ψ. The actual flux magnitude is estimated from the stator voltage and current.

$$|\Psi_s| = \sqrt{{\Psi_{ds}^s}^2 + {\Psi_{qs}^s}^2} \tag{30}$$

Where,

$$\Psi_{ds}^s = \int (v_{ds}^s - R_s i_{ds}^s)\, dt \tag{31}$$

and

$$\Psi_{qs}^s = \int (v_{qs}^s - R_s i_{qs}^s)\, dt \tag{32}$$

The torque error E_{Te} is generated by comparing the desired torque T_e^* and actual torque T_e.

$$T_e = \frac{3P}{4}\left(\Psi_{ds}^s\, i_{qs}^s - \Psi_{qs}^s\, i_{ds}^s\right) \tag{33}$$

The hysteresis band flux controller processes the flux error E_Ψ and generates two levels of output H_Ψ, as flux increase (+1) or decrease (-1). The band width of the controller is 2HB.

$$H_\Psi = +1 \quad for \;\; E_\Psi > -HB_\Psi \tag{34}$$

$$H_\Psi = -1 \quad for \;\; E_\Psi < -HB_\Psi \tag{35}$$

The actual stator flux is Ψ_s controlled within the hysteresis band. The hysteresis band torque controller processes the torque error E_{Te} and generates three levels of output H_{Te}, as increase (+1), decrease (-1) or equal (0).

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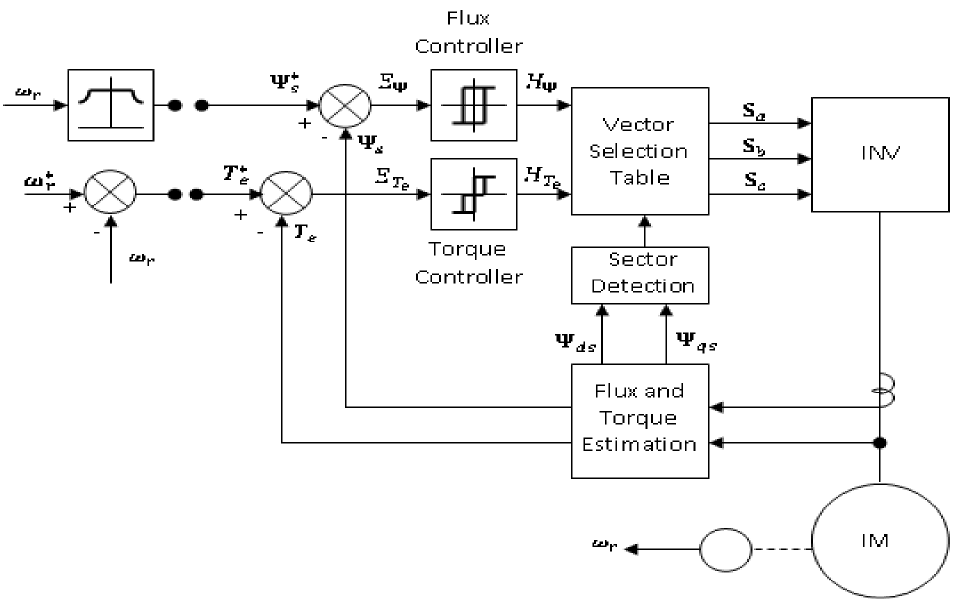

Fig 6. Direct torque control

$$H_{T_e} = +1 \qquad for \;\; E_{T_e} > +HB_{T_e} \qquad (36)$$
$$H_{T_e} = -1 \qquad for \;\; E_{T_e} < -HB_{T_e} \qquad (37)$$
$$H_{T_e} = 0 \;\; for \;\; -HB_{T_e} < E_{T_e} > +HB_{T_e} \qquad (38)$$

The sector is detected by using the flux angle γ.

$$\gamma = \tan^{-1}\left(\frac{\Psi_{qs}^s}{\Psi_{ds}^s}\right) \qquad (39)$$

Based on flux angle, taking the first sector as – 30° to + 30°, the six sectors are shown in Fig 7.

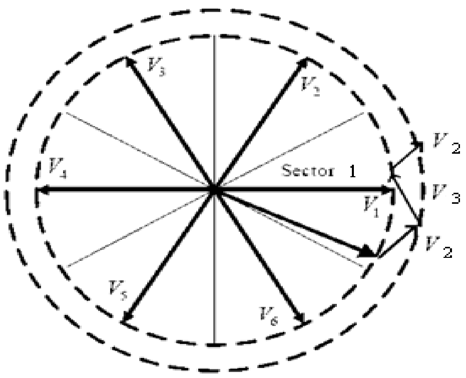

Fig 7. Sectors and movement of flux vector

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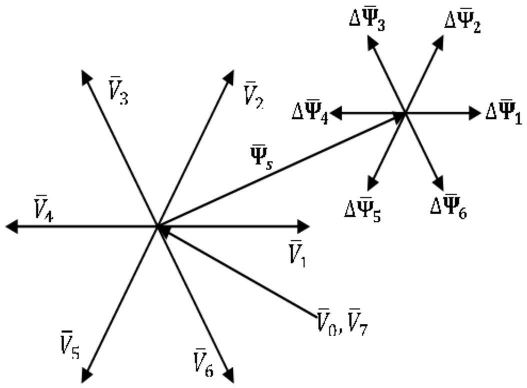

Fig 8. Voltage vector and corresponding stator flux variation

The voltage vector and corresponding stator flux variation is shown in Fig.8. To vary the magnitude of stator flux and developed torque, the voltage vector is selected based on equation (26), Fig 7 and Fig 8 [5]. If the stator flux vector is in first sector. To increase the flux and torque voltage vector V_2 is selected. To decrease the flux and increase the torque voltage vector V_3 is selected. To decrease the flux and torque the voltage vector V_5 is selected. And to increase the flux and decrease the torque the voltage vector V_6 is selected.

The voltage vectors to be selected for variation of stator flux and torque in each sector is identified as above and it is given in Table I [5], [10], [11].

TABLE I
VECTOR SELECTION TABLE

Flux	**Torque**	**Sector**					
		1	**2**	**3**	**4**	**5**	**6**
H_Ψ = +1	**H_{Te} = +1**	V_2	V_3	V_4	V_5	V_6	V_1
	H_{Te} = 0	V_0	V_7	V_0	V_7	V_0	V_7
	H_{Te} = -1	V_6	V_1	V_2	V_3	V_4	V_5
H_Ψ = -1	**H_{Te} = +1**	V_3	V_4	V_5	V_6	V_1	V_2
	H_{Te} = 0	V_7	V_0	V_7	V_0	V_7	V_0
	H_{Te} = -1	V_5	V_6	V_1	V_2	V_3	V_4

V. SIMULATION

To compare the vector control and direct torque control of induction motor, simulations are carried out by using Matlab / Simulink. For simulation a 50HP, 460V, 60 Hz star connected three phase induction motor has been taken and its rated parameters are R_s = 0.087, R_r = 0.228, L_{ls} = 0.8 mH, L_{lr} = 0.8 mH and L_m = 34.7mH. Motor inertia J = 1.662 kg m^2, friction factor B = 0.1 Nm.sec/rad.

The simulations are carried out for three cases.

Case.1. Constant speed (1300 rpm) at no load,

Case.2. Step change in speed (600 to 1300 rpm at 3 sec) at no load.

Case.3. Step change in load (no load to 100 Nm) at constant speed (1300 rpm).

The speed response, stator current response and the torque response are plotted for vector control and direct torque control methods.

VI. RESULTS

Results of simulations of vector control and direct torque control are shown in Fig.9 - 11.

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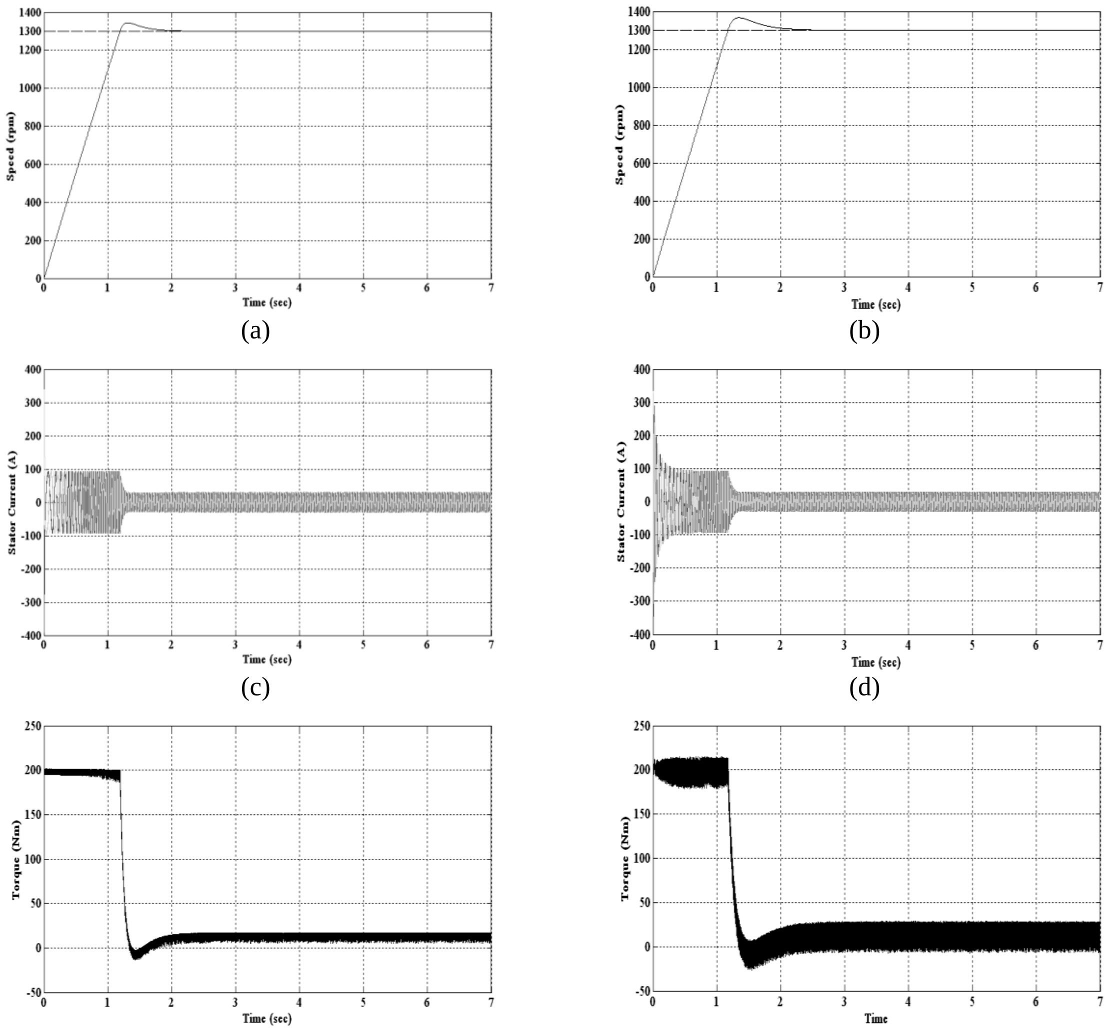

(a) (b)

(c) (d)

(e) (f)

Fig.9.Case.1. Constant Speed and No load
(a), (b) VC and DTC Speed Response
(c), (d) VC and DTC Current Response
(c), (d) VC and DTC Torque Response

Fig.9.(a) and Fig.9.(b) show the speed response at constant speed 1300 rpm under no load. Fig.9.(c) – Fig.9.(e) show the corresponding current and torque response.

Fig.9.(a) and Fig.9.(b) show that the induction motor speed response using vector control has less overshoot during starting settling time compared with direct torque control. In vector control the speed reaches 1344.9 rpm at 1.3129sec and then settled in the steady state speed of 1300 rpm at 2.369 sec. In direct torque control the speed reaches 1366.5 rpm at 1.352 sec, and then it settled in the steady state speed of 1300 rpm at 2.828 sec.

Fig.9.(c) and Fig.9.(d) show that vector control has less stator current transient during starting. The torque response in Fig.9.(e) and Fig.9.(f) show that vector control and direct torque control has the torque ripple of 11Nm and 28Nm respectively.

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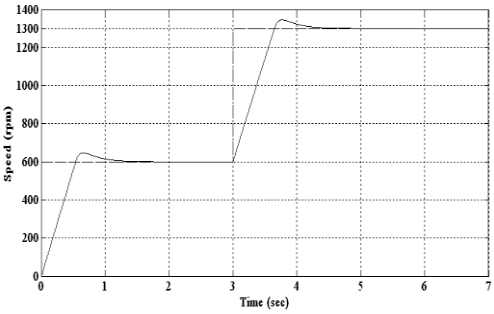
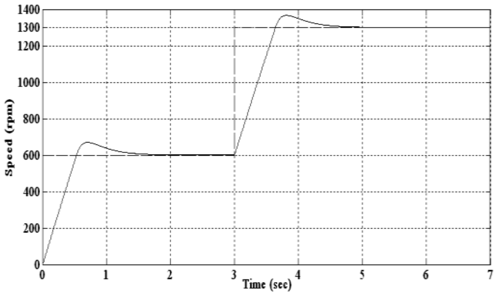


(a)



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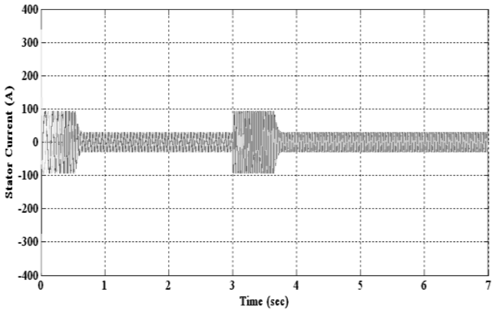
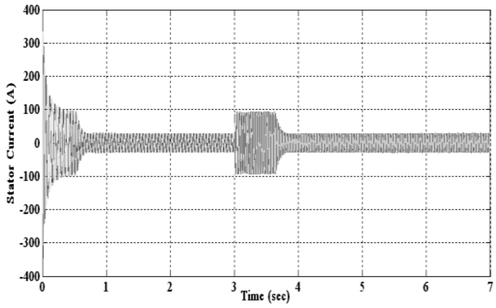
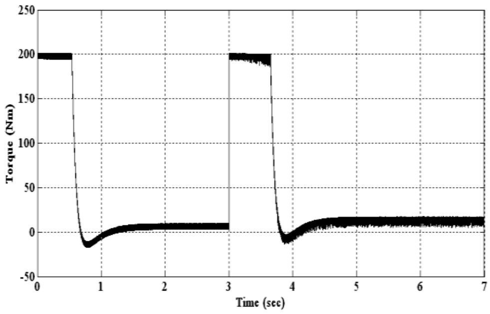


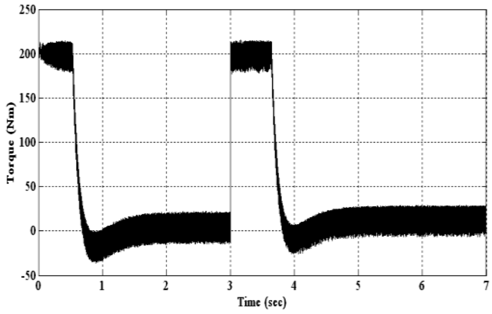
(c)



(d)



(e)



(f)

Fig.10.Case.2. Step Change in Speed and No load
(a), (b) VC and DTC Speed Response
(c), (d) VC and DTC Current Response
(c), (d) VC and DTC Torque Response

Fig.10.(a) and Fig.10.(b) show the speed response for change in speed from 600 rpm to 1300 rpm at 3 sec, under no load. Fig.10.(c) – Fig.10.(e) show the corresponding current and torque response.

Fig.10.(a), (b) show that vector control has quick speed response than direct torque control. . In vector control the speed reaches 646.85 rpm at 0.663 sec and then settled in the steady state speed of 600 rpm at 1.84 sec. The reference speed is changed from 600 rpm to 1300 rpm at 3 sec. The speed reaches 1344.85 rpm at 3.773 sec, and then it comes to 1300 rpm at 5.92 sec. In direct torque control the speed reaches 669.27 rpm at 0.7056 sec and then settled in the steady state speed of 600 rpm at 2.595 sec. After the reference speed is changed, it reaches 1366.5 rpm at 3.818 sec, and then it comes to 1300 rpm at 6.474 sec.

Fig.10.(c), (d) show that vector control has less stator current transient during starting and speed change. The torque response shown in Fig.10.(e) and Fig.10.(f) show that direct torque control has more ripple.

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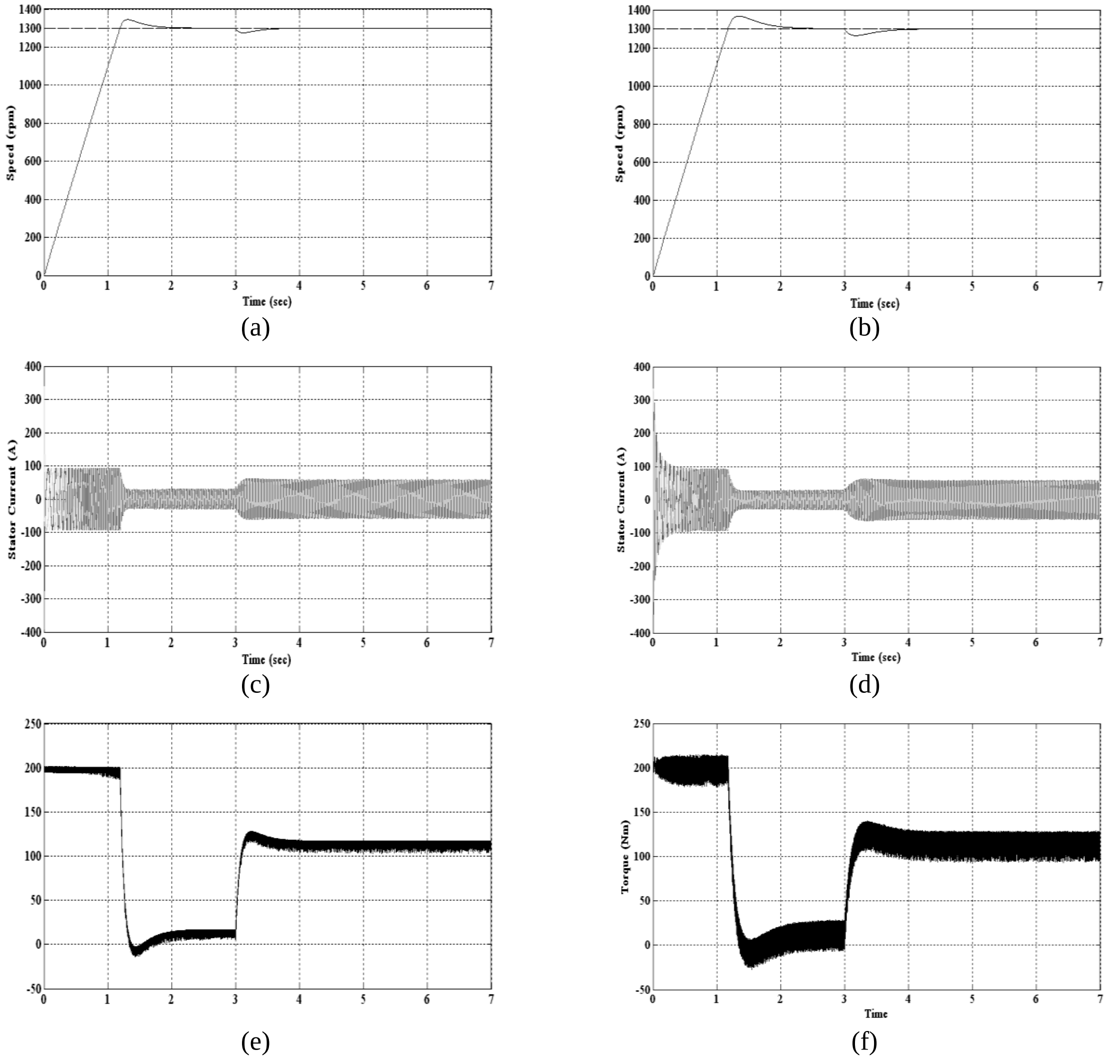

Fig.11.Case.3. Step Change in Load and Constant Speed
(a), (b) VC and DTC Speed Response
(c), (d) VC and DTC Current Response
(c), (d) VC and DTC Torque Response

Fig.11.(a) and Fig.11.(b) show the speed response for change in load from no load to 100 Nm at 3 sec and constant speed 1300 rpm. Fig.11.(c) – Fig.11.(e) show the corresponding current and torque response.

The speed decreases when the load is applied and then it comeback to the steady speed. After the load is applied, the speed decrease to 1275.5 rpm at 3.121sec and then settle in the steady state speed of 1300 rpm at 5.288 sec in vector control. In direct torque control the speed decrease to 1264.5 rpm at 3.175 sec and then settle in the steady state speed of 1300 rpm at 5.304 sec.

The torque response in Fig.11.(e) and Fig.11.(f) show that vector control and direct torque control has the torque ripple of 12 Nm and 33 Nm respectively. After load the torque ripple increased in both methods. The torque ripple is high in direct torque control.

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VII. CONCLUSION

The result shows the performance similarities and differences between vector control and direct torque control methods. The dynamic response of both methods is good. Torque ripple is more in direct torque control method. It is due to the hysteresis band controller. The parameter sensitivity is low in direct torque control. The direct torque control is very simple. The vector control uses more transformation and the architecture is complex. Each method is having its advantages and disadvantages. So it is concluded as the selection of control method is based on particular application of the drive.

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