A Comparative Study between Field Oriented Control and Direct Torque Control of AC Traction Motor

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***Abstract*—The polyphase induction motor has been the motor of choice for electric traction drive. This paper presents the comparison of performance analysis between direct torque control (DTC) and field oriented control (FOC) of induction motor drive for high rating motor. These two approaches belong to family of vector control and offer solutions to high performance drives. In this paper author(s) implemented DTC and FOC utilizing MATLAB/ SIMULINK to simulate dynamics of induction motor to generate results for evaluation. The apparent comparison of these two vector control methods is shown with simulation results.**

Keywords-Field Oriented Control, Direct Torque Control, Induction Motor, MATLAB Simulation

I. Introduction

The AC motors serving Indian Railways are three phase induction motor drives [1]. The squirrel cage rotors type of induction motor drive used for traction is controlled by various vector control techniques [2][3]. Two of the various techniques used for controlling the machine's torque and speed are direct torque control (DTC) and field oriented control (FOC). Field Oriented Control is the first and most popular vector control method [2][4]. Both FOC and DTC are based on the decoupling between the current components used for generating magnetizing flux and torque [5]. The decoupling allows the induction motor to be controlled as a simple DC motor. In the middle of 80s new strategies for the torque control of induction motor was presented by I. Takahashi [6][7]. This new control strategy proposed to replace motor decoupling and linearization via coordinate transformation, by hysteresis controllers, which corresponds very well to on-off operation of the inverter semiconductor power devices. These methods are referred to as Direct Torque Control (DTC).

Vector control method for high rating motor is not readily available in the literature. The objective of this paper is to compare the performance of FOC and DTC when applied to high power rating induction motor drive to identify the advantages and disadvantages that can help to make a choice between them for a particular application. This paper presents the mathematical model of induction motor followed by elucidating the field oriented control and direct torque control scheme [8]. Then numerical simulations are presented and analyzed to emphasize the drive performance obtained for these two methods.

II. Mathematical Model of Induction Motor

The three phase squirrel cage induction motor in synchronous rotating reference frame is represented by the figure 1 [2] [9].

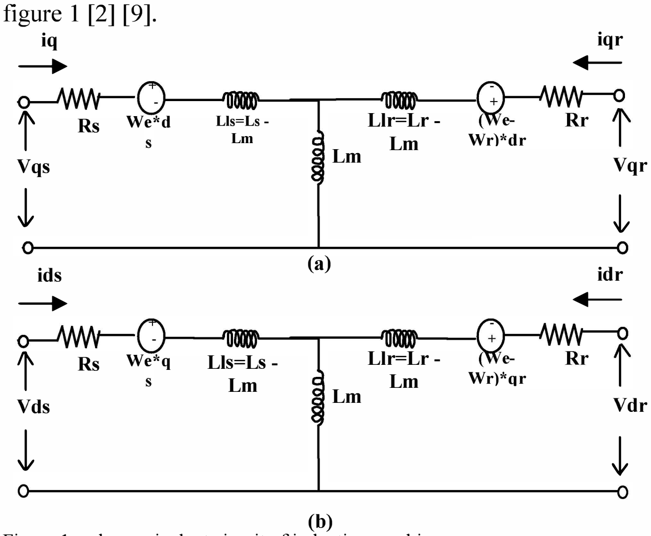

Figure 1. d-q equivalent circuit of induction machine

Figure 1 shows the d-q equivalent circuit that satisfy (1) to (5)

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + (\omega_e - \omega_r)\psi_{dr} \quad (1)$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - (\omega_e - \omega_r)\psi_{qr} \quad (2)$$

$$\psi_{qr} = L_{lr} i_{qr} + L_m(i_{qs} + i_{qr}) \quad (3)$$

$$\psi_{dr} = L_{lr} i_{dr} + L_m(i_{ds} + i_{dr}) \quad (4)$$

$$T_e = \frac{3 * P * L_m}{2 * 2 * L_r} * (\varphi_{dr} i_{qs} - \varphi_{qr} i_{ds}) \quad (5)$$

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Where V_{qr} & V_{dr}, φ_{qr}, φ_{dr}, i_{dr}, i_{ds}, are respectively the motor voltages, fluxes and currents in d-q coordinates; ω_r is the electrical angular speed and Te is the electromagnetic torque. Regarding motor parameters P is number of poles, R_r is the rotor resistance, L_r is rotor inductance and L_m is mutual inductance.

Equations (1)–(5) represent the standard dynamical model of an IM, where the saturation of the machine's magnetic material, the changes of the rotor resistance due to the skin effect, and the temperature changes of the stator resistance are neglected.

III. Field Oriented Control

FOC control utilizes the position of the rotor combined with two-phase currents to generate a means of instantaneously controlling the torque and flux. Field-oriented controllers require control of both magnitude and phase of the AC quantities and are, therefore, also referred to as vector controllers [9] [10]. FOC produces controlled results that have a better dynamic response to torque variations in a wider speed range as compared to other scalar methods. Also, FOC control can induce a high torque at zero speed [2]. A block diagram of vector controlled induction motor drive is shown in figure 2. The induction motor is fed by a current- regulator. The motor drives a mechanical load characterized by inertia J, friction coefficient B, and load torque, T [10]. The speed control loop uses a proportional-integral controller to produce the quadrature axis current reference i_q* which controls the motor torque. The motor flux is controlled by the direct-axis current reference i_d*[11]. Block d-q to abc is used to convert i_d* and i_q* into current references i_a*, i_b*, and i_c* for the current regulator.

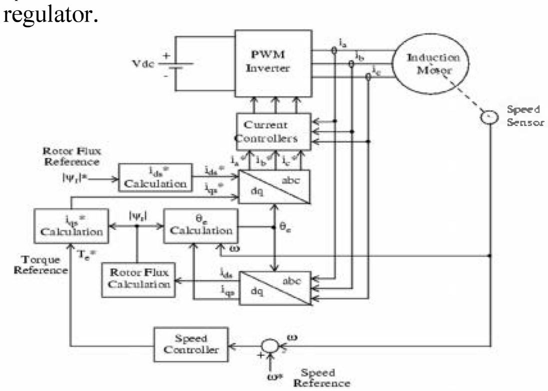

Figure 2. Block diagram of field oriented control of induction machine

In this mode of operation, control of the torque and flux is decoupled such that the d-axis component of the stator current controls the rotor flux magnitude and the q-axis component controls the output torque [12].

The required d-axis component of the stator current, i_{ds} , to achieve a given rotor flux magnitude demand, $\lambda *_{dr}$, can be determined from (6)

$$i_{ds}^* = \frac{|\psi r|^*}{L_m} \quad (6)$$

The required q-axis component of the stator current i_{qs}, for a given torque demand (T_e*), can be determined from (7).

$$i_{qs}^* = \frac{2}{3}\cdot\frac{2}{p}\cdot\frac{L_r}{L_m}\frac{T_e^*}{|\psi r|est} \quad (7)$$

IV. Direct Torque Control

A direct torque controlled (DTC) induction motor drive is supplied by a voltage source inverter and it is possible to control directly the stator flux linkage λ_s (or the rotor flux λ_r or the magnetizing flux λ_m) and the electromagnetic torque by the selection of an optimum inverter voltage vector. [13] Direct torque control of induction motors is described by the basic functional blocks as shown in figure 3. By means of the use of closed loop estimator, the instantaneous values of flux and torque are calculated from stator variables [14] [15].

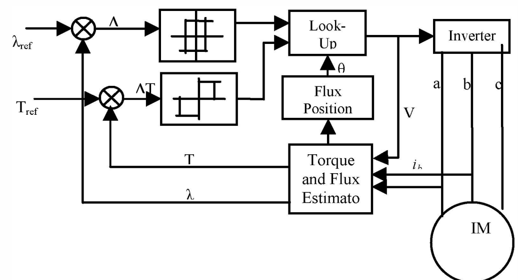

Figure 3. Block diagram of direct torque control of induction machine

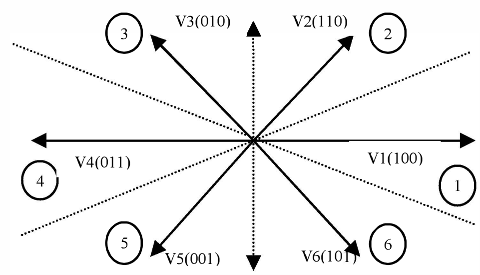

Figure 4. Stator flux vector locus and different possible switching voltage vectors

The stator flux and torque magnitudes are compared with respective estimated values and errors are processed through hysteresis controllers. The output of the flux and torque comparator is used for the inverter optimal switching table. The electromagnetic torque in the three phase induction machines can be expressed as in (8):

$$Te = 3/2\ P|\psi s|.|is|.\sin(\alpha s - \rho s) \quad (8)$$

Where ψ_s is the stator flux, is is the stator current, P the number of pairs of poles, ρs is the stator flux angle. If the stator flux modulus is kept constant and the angle ρs is changed quickly, then the electromagnetic torque is directly controlled [14]. The same expression can be obtained for the electromagnetic torque as in (9):

$$Te = \frac{3}{2}P\frac{Lm}{LsLr - Lm^2}|\psi r|.|\psi s|.\sin(\rho s - \rho r) \quad (9)$$

Decoupled control of the stator flux modulus and torque is achieved by acting on the radial and tangential components respectively of the stator flux-linkage space vector in its locus. Figure 4 shows the voltage space vectors employed for DTC scheme. The main concept for employing a switching table in DTC is that the measured values of stator flux and electromagnetic torque are compared to reference values, i.e. $\boldsymbol{\lambda}_s*$ and $T_{em}*$ through hysteresis controller.

V. SIMULATION RESULTS AND ANALYSIS

The simulations were executed to obtain comparative results of both control schemes. Figure 5 & figure 6 shows the Simulink model of the FOC and the DTC scheme respectively.

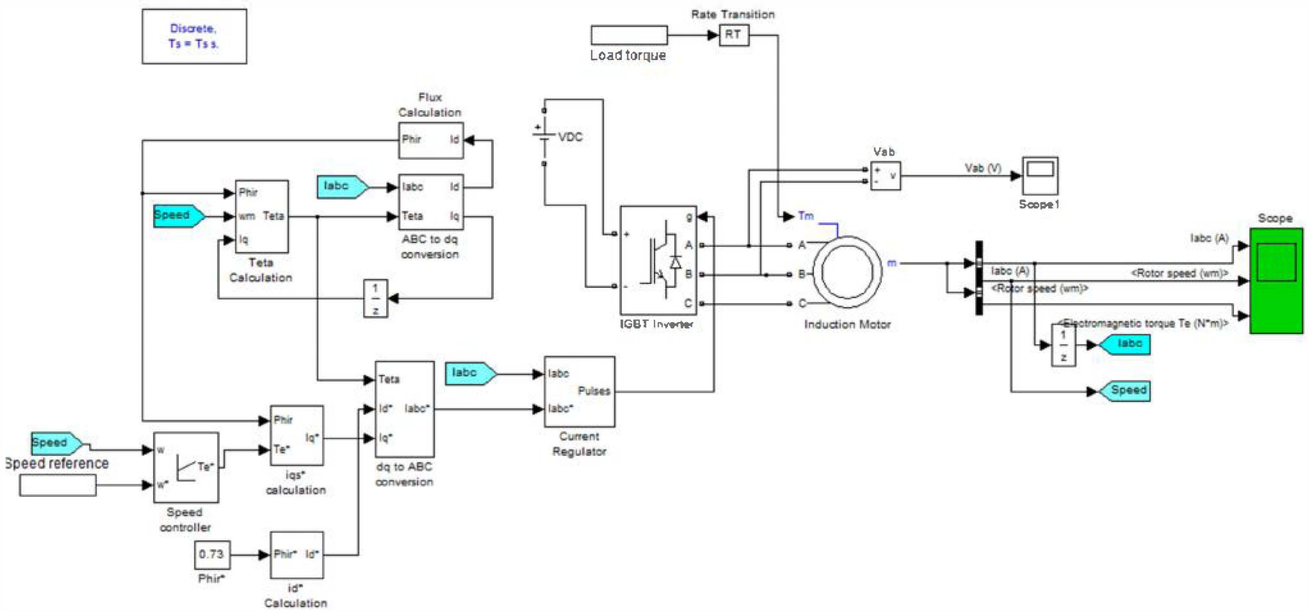

Figure 5. Simulink model of field oriented control of induction motor

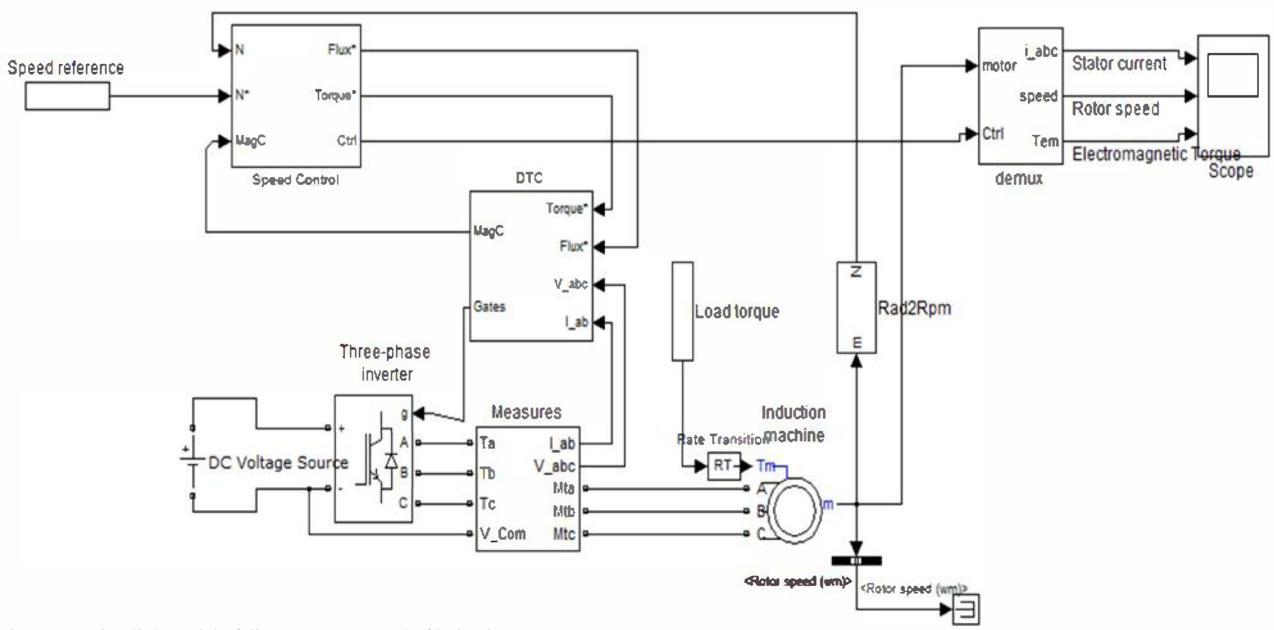

Figure 6. Simulink model of direct torque control of induction motor

The simulation results for both methods are shown in figure 7 to figure 13. The load is applied at 0.5 second. The results for electromagnetic torque, rotor speed and stator currents at no load condition for the reference speed at 180 rad/sec shown in figure 7. Similarly the results for electromagnetic torque, rotor speed and stator currents at 50% load condition and full load for the reference speed at 180 rad/sec are also shown in figure 8 and figure 9.

Table I shows the comparison between the time required to attain steady state and steady state torque oscillations for FOC and DTC schemes with reference to results shown in figure7 to figure 9 for different percentage loading at a given speed of 180 rad/sec. In DTC scheme, time to attain steady state remain relatively constant at 0.55 seconds. Whereas in case of FOC time to attain steady state increases with the increase in percentage loading.

It is observed that the torque oscillations in FOC control scheme are negligible whereas in DTC scheme oscillations in torque are observed. These oscillations are relatively less at no load and then become nearly constant with the increase in percentage loading. Also, it is found that the distortion of motor current is higher in case of DTC.

TABLE I. COMPARISON OF CONTROL SCHEMES AT DIFFERENT LOADS

% Loading	Type of Control Scheme	Time to attain steady state(s)	Steady state torque oscillations (%)
No Load	FOC	0.72	±1.2
	DTC	0.55	±6.25
50% load	FOC	0.78	±1.56
	DTC	0.55	±7.5
Full Load	FOC	0.82	±1.56
	DTC	0.55	±7.5

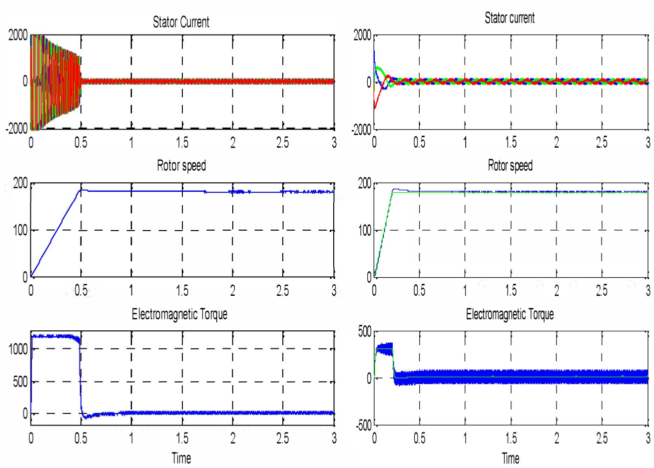

Figure 7. Simulink plot for FOC (left) and DTC (right) showing three phase stator current, speed and electromagnetic torque for no load at 180rad/sec speed.

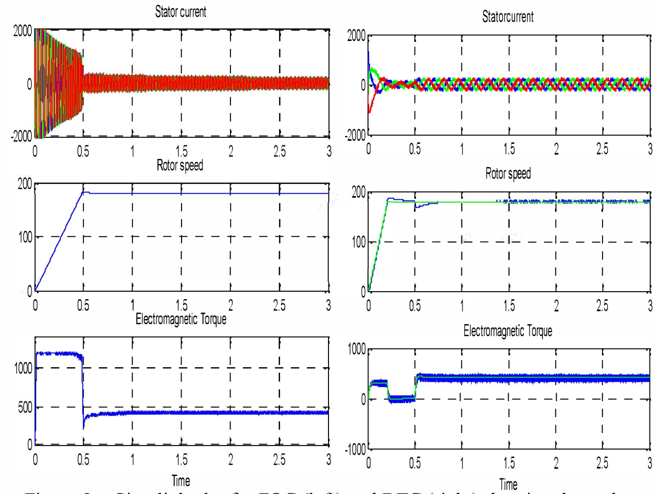

Figure 8. Simulink plot for FOC (left) and DTC (right) showing three phase stator current, speed and electromagnetic torque for half load (400Nm) at 180rad/sec speed.

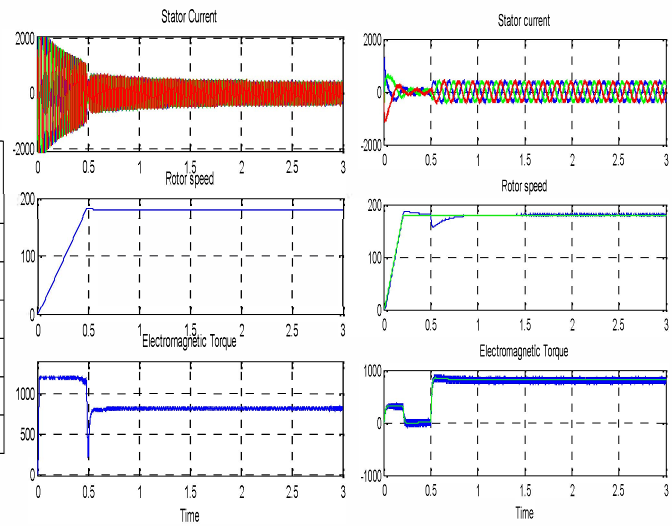

Figure 9. Simulink plot for FOC (left) and DTC (right) showing three phase stator current, speed and electromagnetic torque for full load (800Nm) at 180rad/sec speed.

Table II shows the comparison between the time required to attain steady state and steady state torque oscillations for FOC and DTC control schemes with reference to results shown in figure10 to figure 13 for different speeds at full load (800 Nm). Different speeds taken are: 50 rad/s, 100 rad/s, 150 rad/s and 180 rad/s. Table II shows that time to attain steady state torque is approximately constant for different speeds for both schemes. Also, the comparison shows that in DTC scheme torque attains steady state faster than FOC.

Similarly, torque oscillations at low speed are comparatively very high and then decreases with increase in speed for both the control schemes. Also, steady state oscillations in FOC control scheme are much smaller as compared to DTC.

TABLE II. COMPARISON AT DIFFERENT SPEEDS

Different Speeds	Type of Control Scheme	Time to attain steady state(s)	Steady state torque oscillations (%)
50 rad/sec	FOC	0.8	±2.185
	DTC	.55	±11.25
100 rad/sec	FOC	0.82	±2.05
	DTC	.55	±8.25
150 rad/sec	FOC	0.82	±2.05
	DTC	.55	±7.90
180 rad/sec	FOC	0.82	±1.56
	DTC	.55	±7.5

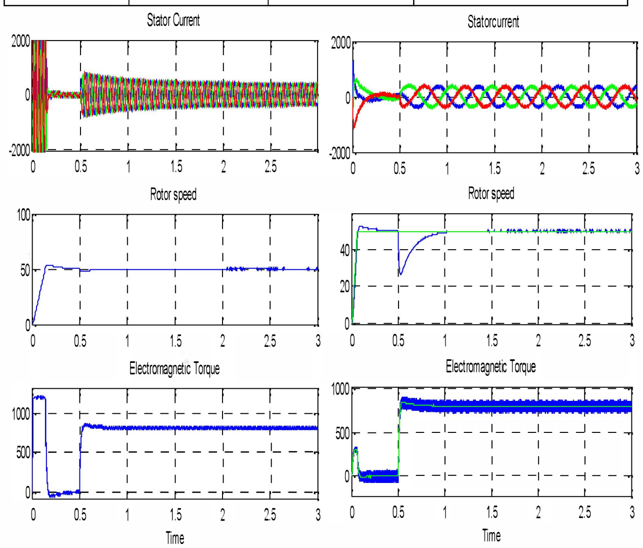

Figure 10. Simulink plot for FOC (left) and DTC (right) showing three phase stator current, speed and electromagnetic torque for full load (800Nm) at 50rad/sec speed.

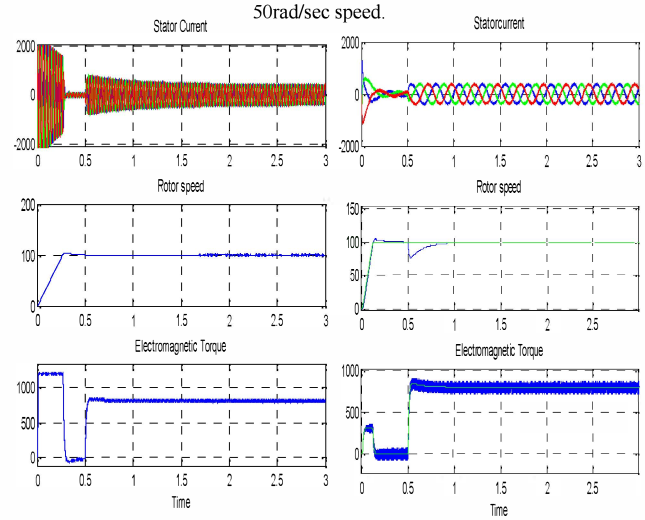

Figure 11. Simulink plot for FOC (left) and DTC (right) showing three phase stator current, speed and electromagnetic torque for full load (800Nm) at 100rad/sec speed.

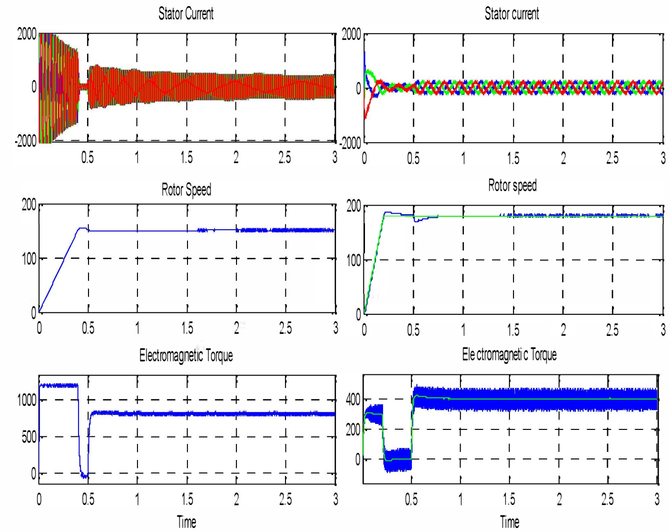

Figure 12. Simulink plot for FOC (left) and DTC (right) showing three phase stator current, speed and electromagnetic torque for full load (800Nm) at 150rad/sec speed.

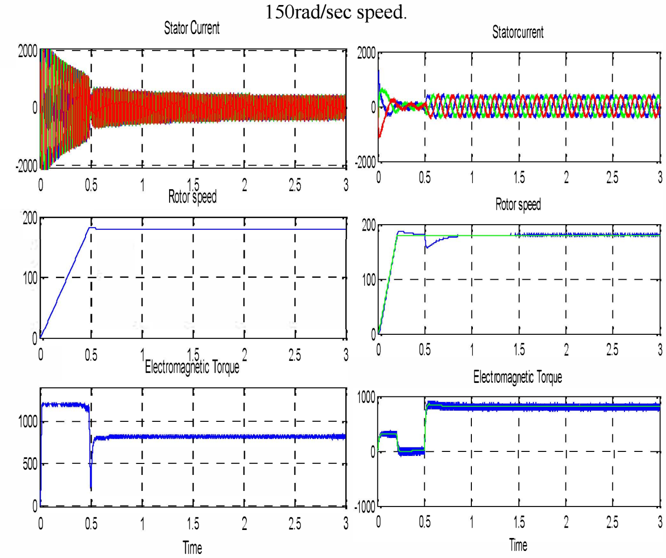

Figure 13. Simulink plot for FOC (left) and DTC (right) showing three phase stator current, speed and electromagnetic torque for full load (800Nm) at 180rad/sec speed

VI. CONCLUSION

This paper presents a comparison between two vector control methods of induction motor drives: Field oriented control and direct torque control. Both methods provide a decoupled control of torque and flux during transients and steady-state. With DTC Control scheme the motor attains steady state much faster but have oscillations in the torque whereas with FOC the oscillations in the torque are much smaller but takes more time to attain steady state. So, depending upon the needs of a particular application one method can be more suitable than the other.

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APPENDIX

The induction machine used in the MATLAB /simulation is 3phase, 60Hz induction machine having the following parameters.

Power output	200HP
Rated Voltage	480V
R_s (stator resistance)	0.01485Ω
R_r (rotor resistance)	0.009295Ω
L_s (stator inductance)	0.0003027H
L_r (rotor inductance)	0.0003027H
L_m (magnetizing inductance)	0.01046H
J (moment of inertia)	3.1Kg m^2
P (number of poles)	4

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