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Simulation as an Effective Tool for the Comparative Evaluation of Field Oriented Control and Direct Torque Control of Induction Motor

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Abstract—This paper presents a comparative study of two most popular control strategies for Induction motor (IM) drives: Field-Oriented Control (FOC) and Direct Torque Control (DTC). The comparison is based on various criteria including basic control characteristics, dynamic performance, and implementation complexity. The study is done by simulation using the Simulink Power System Block set that allows a complete representation of the power section (inverter and IM) and the control system.

Keywords—IM, FOC, DTC, Simulink

I. INTRODUCTION

Variable speed or adjustable torque control of electrical motor drives are crucial components in almost all-modern industrial manufacturing processes. Traditionally variable speed electric machines were based on dc motors, but, for the last 20 years, Ac drives using induction machines are now finding increasing acceptance in various industrial applications because of the performance they can provide.

The development of high performance control strategies for ac drives, driven by industry requirements has followed a rapid evolution during the last two decades. It is now recognized that the two high-performance control strategies for induction motor drives are Field Oriented Control (FOC) [1], [2], [3], [7], [11], [13] and Direct Torque Control (DTC) [4], [5], [6], [8], [9], [10], [12], [14].Using these techniques, both the induction motor and the permanent magnet synchronous motor (PMSM) can be applied even in high performance servo applications that were once the exclusive domain of the dc machine. Both FOC and DTC are strategies allow torque and flux to be decoupled and controlled independently. In the dc machine, this decoupling is obtained in an electromagnetic way by orienting the current with respect to the stator flux using a commutator. In ac machines, this decoupling is obtained by implementing mathematical transformations, thereby avoiding problems due to the commutator. The mentioned control techniques have undergone considerable research over the last 15 years, but several problems remain: FOC is very dependent on knowledge of the rotor time constant when using an induction machine. DTC, in its traditional form, results in a non-constant inverter switching frequency, which may result in high inverter/motor losses. Techniques that fix this problem result in parameter dependent solutions.

The purpose of this paper is to present a comparative study on these two control schemes via simulation using the Simulink power System Block set (PSB) that allows a complete representation of the power section (inverter and IM) and the control system. Control technology of ac motor drives has improved dramatically during the last two decades. This trend owes its progress to the new control techniques and philosophies developed by several researchers around the world. The implementation of those concepts was possible due to technological developments such as the DSP controllers and the new power semiconductors.

II. FIELD ORIENTED CONTROL (FOC)

The vector control philosophy started to be developed around 1970. Several types of vector control are possible: rotor-oriented, rotor-flux-oriented, stator-flux-oriented and magnetizing-flux-oriented. The final objective of the vector control philosophy is to be able to control the electromagnetic torque in a way equivalent to that of a separately excited dc machine. This is possible if the machine control is considered in a synchronously rotating reference frame, where the variables appear as dc quantities in steady state: Field-oriented control enables control over both the excitation flux-linkage and the torque-producing current in a decoupled way. However, only the rotor-flux-oriented control yields complete decoupling. Choosing a different flux orientation may outweigh the lack of complete decoupling for some special applications. Here, only the rotor-flux-oriented type of control, also termed "Field-Oriented Control" (FOC), is considered. FOC can be implemented as indirect (feed-forward) or direct (feedback) depending on the method used for rotor flux identification. The direct FOC determines the orientation of the air-gap flux by use of a hall-effect sensor, search coil or other measurement techniques. However, using sensors is expensive because special modifications of the motor are required for placing the flux sensors. Furthermore, it is not possible to directly sense the rotor flux. Calculating the rotor flux from a directly sensed signal may result in inaccuracies at low speed due to the dominance of stator resistance voltage drop in the stator voltage equation and inaccuracies due to variations on flux level and temperature.

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The electromagnetic torque can be expressed in more general form relating the d-q components of variables are as follows:

$$T_e = \frac{3}{2}\frac{P}{2}L_m\left(i_{qs}i_{dr} - i_{ds}i_{qr}\right) \tag{1}$$

The above equation gives the complete model of the electromechanical dynamics of induction motor in synchronous frame. Electromagnetic torque is given in terms of stator and rotor current space-phasor. The rotor current space-phasor can be eliminated from this equation, and the torque can be expressed in terms of stator current space-phasor and any of the three flux-linkage space-phasor. Following are the methods of vector control depending on the flux-linkage space-phasor selected for the control Following are the methods of vector control depending on the flux-linkage space-phasor selected for the control:

Air gap-flux oriented control, Stator-flux oriented control and Rotor-flux oriented control

All of the above three methods of vector control are similar as far as the transient torque-response and parameter-sensitivity is concerned. However, the rotor-flux oriented control scheme has the following advantages over the other two methods:

- Control-scheme is simpler to implement.
- There is no pullout torque if there is no limitation on the stator current supply.

The rotor-flux oriented vector control method can further be classified as follows:

- " Flux vector method or feedback method, where magnetic flux vector of induction motor is fed back and stator current is controlled on the basis of flux vector (direct vector control). This method requires flux sensors or flux estimation model for the accurate estimation of magnitude and position of flux vector.
- " Slip frequency control method or feed-forward method, where angular velocity of rotor is fed back and is added to calculated slip speed to predict the position of flux vector and thus to control the stator current vector (indirect vector control).

In contrast to direct vector control, the indirect vector control is the most popular method in industrial applications, meeting the requirement of wide speed range and fast torque response. The next section deals with the rotor-flux oriented indirect vector control method. The indirect vector control method is essentially the same as the direct vector control, except the unit vector signal ($cos\,\theta_e$ and $sin\,\theta_e$) generation. The $d^s - q^s$ axis is fixed on the stator and the $d^r - q^r$ axis is fixed on the rotor, which moves at a speed of ω_r. The synchronously rotating axis $d^e - q^e$ is rotating ahead of the $d^r - q^r$ axis by the positive slip angle θ_{sl} corresponding to slip frequency ω_{sl} Since the rotor pole is directed on the d^e axis and $\omega_e = \omega_r + \omega_{sl}$, we can write

$$\theta_e = \int \omega_e\,dt = \int \left(\omega_r + \omega_{sl}\right)dt = \theta_r + \theta_{sl} \tag{2}$$

Note that the rotor pole position is not absolute, but is slipping with respect to the rotor at frequency ω_{sl}. For decoupling control, the stator flux component of current i_{ds} should be aligned on the d^e axis, and the torque component of current, i_{qs} should be on the q^e axis.

The stator and rotor circuit equations of induction motor are as follows

$$v_{qs} = R_s i_{qs} + \frac{d}{dt}\psi_{qs} + \omega\psi_{ds} \tag{3}$$

$$v_{ds} = R_s i_{ds} + \frac{d}{dt}\psi_{ds} - \omega\psi_{qs} \tag{4}$$

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + \left(\omega - \omega_r\right)\psi_{dr} \tag{5}$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - \left(\omega - \omega_r\right)\psi_{qr} \tag{6}$$

Substitute $\omega = \omega_e$ in the above equations to convert them to synchronously rotating frame.

$$0 = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + \left(\omega_e - \omega_r\right)\psi_{dr} \tag{7}$$

$$0 = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - \left(\omega_e - \omega_r\right)\psi_{qr} \tag{8}$$

The rotor flux linkage expressions can be given as

$$\psi_{qr} = L_{lr} i_{qr} + L_m \left(i_{qs} + i_{qr}\right) \tag{9}$$

$$\psi_{dr} = L_{lr} i_{dr} + L_m \left(i_{ds} + i_{dr}\right) \tag{10}$$

From the above equations we can write

$$i_{qr} = \frac{1}{L_r}\psi_{qr} - \frac{L_m}{L_r}i_{qs} \tag{11}$$

$$i_{dr} = \frac{1}{L_r}\psi_{dr} - \frac{L_m}{L_r}i_{ds} \tag{12}$$

The rotor currents in Equations (7) and (8), which are inaccessible, can be eliminated with the help of Equations (11) and (12) as

$$\frac{d}{dt}\psi_{qr} + \frac{R_r}{L_{rr}}\psi_{qr} - \frac{L_m}{L_{rr}}R_r i_{qs} + \omega_{sl}\psi_{dr} = 0 \tag{13}$$

$$\frac{d}{dt}\psi_{dr} + \frac{R_r}{L_{rr}}\psi_{dr} - \frac{L_m}{L_{rr}}R_r i_{ds} - \omega_{sl}\psi_{qr} = 0 \tag{14}$$

Where $\omega_{sl} = \omega_e - \omega_r$ has been substituted. For decoupling control, it is desirable that $\psi_{qr} = 0$ that is, $\frac{d}{dt}\psi_{qr} = 0$ so, the total rotor flux $\hat{\psi}_r$ is directed on the d^e axis.

By substituting the above conditions in Equation (13) and (14), we get

$$\frac{L_{rr}}{R_r}\frac{d}{dt}\hat{\psi}_r + \hat{\psi}_r = L_m i_{ds} \tag{15}$$

$$\omega_{sl} = \frac{L_m}{\hat{\psi}_r}\frac{R_r}{L_{rr}}i_{qs} \tag{16}$$

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Where $\hat{\psi}_r = \psi_{dr}$ has been substituted. If rotor flux $\hat{\psi}_r = constant$, which is usually the case, then from Equation (15)

$$\hat{\psi}_r = L_m i_{ds} \qquad (17)$$

In other words, the rotor flux is directly proportional to current i_{ds} in steady state. For the implementation of rotor-flux oriented indirect vector control, current regulated or voltage-regulated PWM VSI can be used.

A. Simulink Implementation of FOC of IM

The Simulink model for classical rotor-flux oriented indirect vector control of induction motor is shown in Fig.1. It mainly consists of four blocks: induction motor model, PWM inverter, and command voltage generator and vector controller. The command inputs to the model are reference speed and torque.
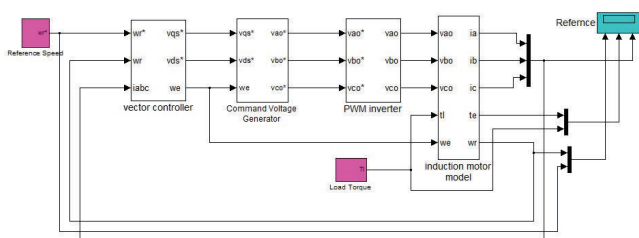
Fig. 1. Simulink model of indirect FOC

The PWM inverter (as shown in Fig. 2) first compares the reference voltage V_{ref} to the command voltages to generate PWM signals for each phase, then uses these signals to drive three Simulink "Switch" blocks switching between $\frac{+V_{dc}}{2}$ and $\frac{-V_{dc}}{2}$ (V_{dc}:Dc Link Voltage). The vector controller block is shown in Fig. 3. The reference speed is compared to the actual rotor speed. The PI controller processes the error and produces the torque-producing component of reference current. This current is again compared to actual motor torque producing current. The PI controller processes this error and produces v_{qs}^*."Go to" and "From" blocks are used to reduce the complexity of connections. The flux estimated by the Blaschke model (as shown in Fig. 4) is compared to reference flux (produced by the flux versus speed table) to generate i_{ds}^*.The error between i_{ds}^* and i_{ds} is processed by the PI to generate v_{qs}^*. The generation of ω_e is also shown in the figure. The feed-forward Counter EMF (CEMF) signals are injected into the i_{ds} and i_{qs} loops to overcome the small coupling effect.

The vector controller block is shown in Fig. 3. The reference speed is compared to the actual rotor speed. The PI controller processes the error

III. DIRECT TORQUE CONTROL (DTC)

Direct Torque and Flux Control (DTFC), also termed Direct Torque Control (DTC), has been developed by German and Japanese researchers for use in torque control of high power servo drives. The publication of the DTC theory actually goes back to 1971. Recently, it has provided an industrial alternative to the field oriented control strategy. DTC is a control philosophy exploiting the torque and flux producing
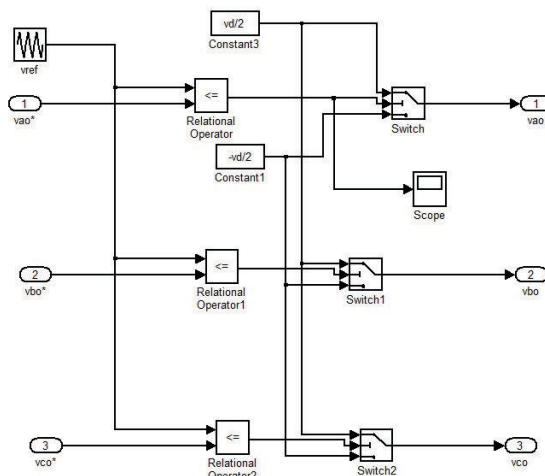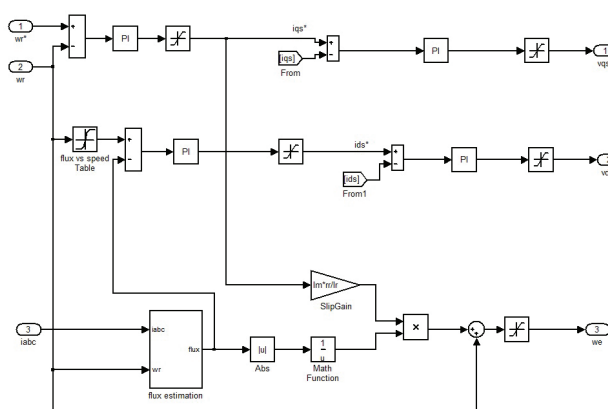

Fig. 2. Simulink model of PWM inverter

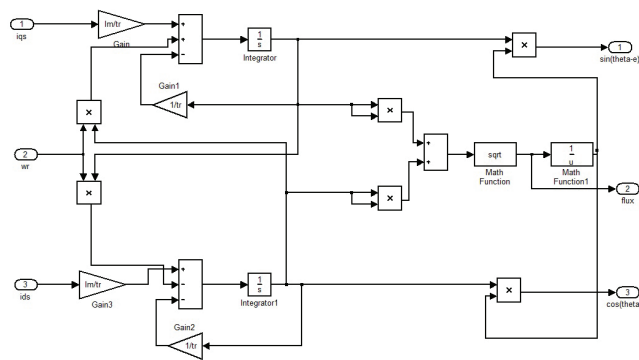Fig. 3. Simulink model of vector controller block

Fig. 4. Simulink model of Blaschke flux estimation block

capabilities of ac machines when fed by a simple voltage source inverter, that does not require current regulation loops, still attaining similar performance to that obtained from a vector control drive [Buja 98]. In a direct torque controlled (DTC) induction motor drive supplied by a voltage source inverter, it is possible to control directly the stator flux linkage ψ_s(or the rotor flux ψ_r or the magnetizing flux ψ_m)and the electromagnetic torque by the selection of an optimum inverter

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voltage vector. The selection of the voltage vector of the voltage source inverter is made to restrict the flux and torque error within their respective flux and torque hysteresis bands and to obtain the fastest torque response and highest efficiency at every instant. In Direct Torque Control, fast torque response can be obtained by selecting the optimal switching state of the PWM inverter if the flux magnitude is kept constant. The electromagnetic equation of induction machine can be written in the following form:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{\sigma L_s L_r}\,|\psi_r|\,|\psi_s|\sin\eta \qquad (18)$$

Where $\bar{\psi}_s$ is stator flux linkage space vector and $\bar{\psi}_r$ is the rotor flux space vector and η is the angle between them. Both these space vectors are expressed in the stationary reference frame. It is possible to put the above equation in the following form using the phasor diagram, which is shown in Fig. 5
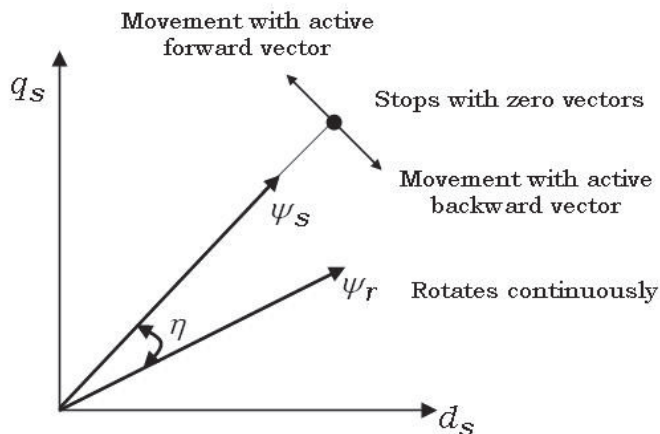

Fig. 5.   Rotor and stator flux linkage space phasor

In contrast to a vector controlled induction motor drive, where the stator currents are used as control quantities, in the direct controlled drive, the stator flux-linkages are controlled. It should be noted that $|\bar{\psi}_r|$ is constant. The stator flux linkage position can be adjusted by selecting the appropriate stator flux vector. This can be achieved considering the following:
The stator voltage can be represented by

$$v_{qds} = R_s i_{qds} + \frac{d\psi_{qds}}{dt} \qquad (19)$$

If we assume that the stator resistance voltage drop is negligible, then the following equation is valid:

$$v_{qds} = \frac{d\psi_{qds}}{dt} \qquad (20)$$

From the Equation (19) it can be seen that the inverter voltage directly force the stator flux, the required stator-flux locus will be obtained by choosing the appropriate inverter switching state. Thus the stator-flux linkage move in space in the direction of the stator-voltage space vector at a speed that is proportional to the magnitude of the stator-voltage space vector. By selecting step-by-step, the appropriate stator voltage vector, it is then possible to change the stator flux in the required way.

If an increase of the torque is required, then the torque is controlled by applying voltage vectors that advance the flux-linkage space vector in the direction of rotation. If a decrease in torque is required then zero switching vectors has to apply. In summary if the stator flux vector lies in the k-th sector and the motor is running anticlockwise, torque can be increased by applying stator voltage vectors V_{k+1} or V_{k+2},and decreased by applying a zero voltage vector $V0$ or $V7$.Decoupled control of the torque and stator-flux can be achieved by acting on the radial and tangential components of the stator-voltage space vector in the same directions, and thus can be controlled by the appropriate inverter switching. In general, if the stator flux linkage vector lies in the k-th sector, its magnitude can be increased by using switching vectors V_{k-1}(for clockwise rotation) or V_{k+1} (for anticlockwise rotation), and can be decreased by applying voltage vectors $V_{k-2}$for clockwise rotation) or V_{k+2} (for anticlockwise rotation). The above can be tabulated in the look up table I(Takahashi look-up table)

TABLE I
TAKAHASHI LOOK-UP TABLE

Flux Error Position	Torque Error Position	Sector I	Sector II	Sector III	Sector IV	Sector V	Sector VI
	1	V2(110)	V3(010)	V4(011)	V5(001)	V6(101)	V1(100)
1	0	V7(111)	V0(000)	V7(111)	V0(000)	V7(111)	V0(000)
	-1	V6(101)	V1(100)	V2(110)	V3(010)	V4(011)	V5(001)
	1	V3(010)	V4(011)	V5(001)	V6(101)	V1(100)	V2(110)
0	0	V0(000)	V7(111)	V0(000)	V7(111)	V0(000)	V7(111)
	-1	V5(001)	V6(101)	V1(100)	V2(110)	V3(010)	V4(011)

The inputs to the look-up table are the torque error and the flux error generated by a three-level and a two-level hysteresis comparator respectively. The torque error is 1, if an increase in torque is required, 0 if a decrease is required. That is for anticlockwise rotation:

$$E_{Te} = 1 \quad if \quad T \leq T_{ref} - |\Delta T|$$
$$E_{Te} = 0 \quad if \quad T \geq T_{ref}$$

The flux error is 1 if an increase in the flux is required, 0 if a decrease is required that is:

$$E_{\psi s} = 1 \quad if \quad |\psi_s| \leq |\psi_s^{ref}| - |\Delta \psi_s|$$
$$E_{\psi s} = 0 \quad if \quad |\psi_s| \geq |\psi_s^{ref}| + |\Delta \psi_s|$$

Simulink Implementation of DTC of IM
The Simulink model for classical stator-flux oriented DTC of IM is shown in Fig.6. It consists of four blocks: stationary frame IM model, voltage source inverter, DTC controller and PI controller. Based on the knowledge of FLC, look-up table based on-line tuning PI controller is implemented for outer speed control loop to achieve precision speed control. The VSI (shown in Fig. 7) uses the switching signals generated by the DTC controller to drive three Simulink "Switch" blocks switching between $\frac{+V_{dc}}{2}$ and $\frac{-V_{dc}}{2}$ The o-n conversion block is included in the motor model. The Simulink model for DTC controller is given in Fig. 8. The reference torque is produced by the on-line PI controller and the stator-flux reference value is assigned as 0.5 Wb using "Constant" block. As shown, the DTC contains two different loops corresponding to the stator flux and torque. The reference values for the stator-flux and torque are compared with the actual values, and then

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resulting error values are fed to two level and three level hysteresis controllers respectively. These can be implemented with the Simulink "Relay" blocks. The outputs of the relays together with position of the stator flux are used as the inputs to Takahasi look-up table. The look-up table can be implemented with "Embedded MATLAB Function" block. This block makes use of a simple "If" and "If-else" program.

Fig. 8.   Simulink model DTC Controller block

Fig. 6.   Simulink model for direct torque control of induction motor

Fig. 9.   Simulation results for (a) Stator current of motor (b) Torque response of the motor for 1500 rpm & no-load

Fig. 7.   Simulink model of voltage source inverter

Fig. 10.   Simulation results for Speed response for 1500 rpm at no load

IV. SIMULATION RESULTS

A detailed comparison between the two solutions has been carried out by numerical simulations, where secondary effects, which could mask the switching behavior, are not present. In this way it is possible to make a significant comparison of the steady state and transient performance of the two control schemes.

Simulation Results of FOC of IM

Fig.9&10 shows the simulation results for stator currents; Enlarged view of steady-state stator currents; torque response
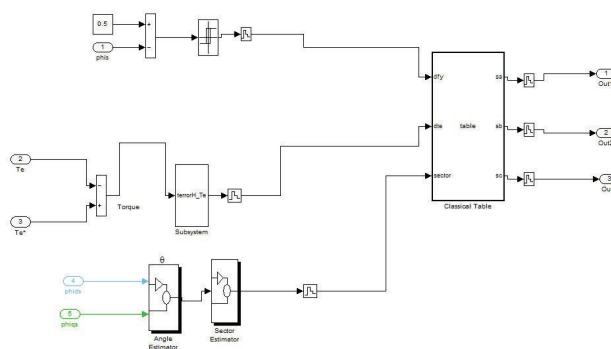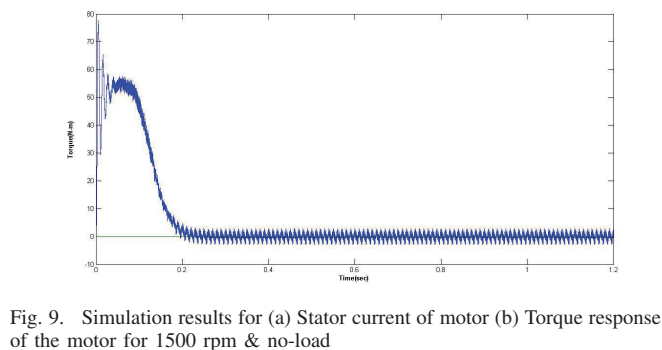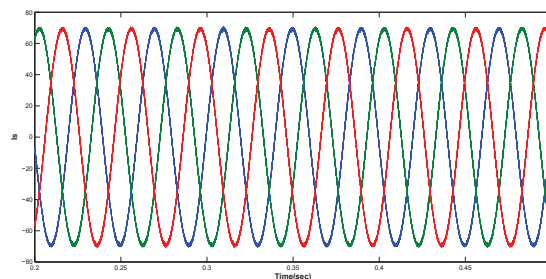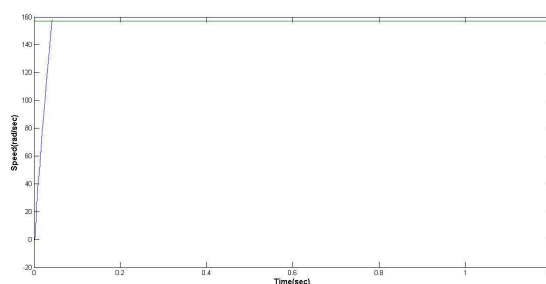
and speed response of IM respectively for no-load condition. The reference speed is at 1500 rpm as shown, the motor takes 0.05 seconds to reach reference speed.

Fig. 11 shows the torque response of indirect vector controlled IM for step-load condition. The reference speed is set at 1500 rpm and a step load of 20 N-m is introduced at 0.8 seconds.

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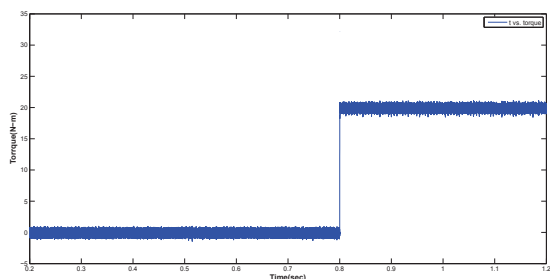Vol:7, No:1, 2013

Fig. 11.   Simulation results for Torque response for a step load of 20 N-m at 0.8 sec.
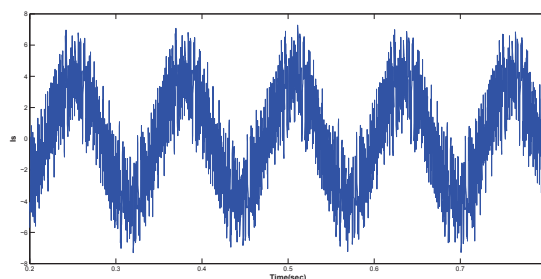

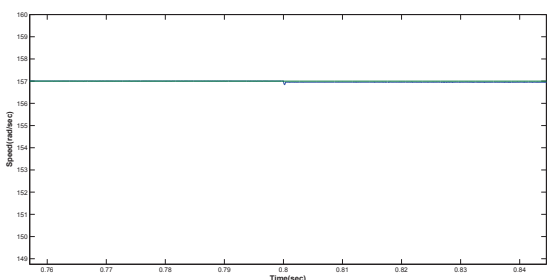Fig. 14.   Simulation results for stator current for 1500 rpm and no-load

Fig. 12.   Simulation results for speed response for a step load of 20 N-m at 0.8 sec.
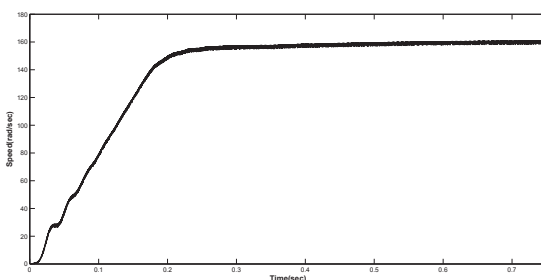

Fig. 15.   Simulation results for speed response for a step load of 20 N-m at 0.8 sec.

Fig. 12 shows the simulation results for motor speed response for FOC for 1500-rpm reference. The motor is loaded with 20 N-m at 0.8 seconds. With this step load, the motor speed reduces slightly and restores back to original value. As observed, the FOC takes approximately 0.2 seconds to restore to original value.

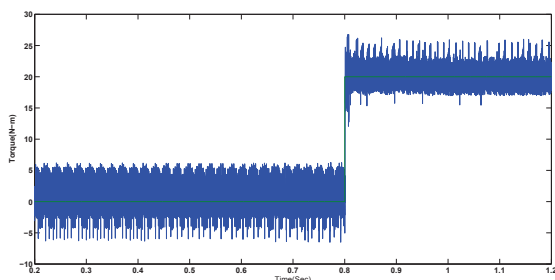**Simulation Results of DTC of IM**

Fig. 13.   Simulation results for Torque response of the motor for 1500 rpm and no-load

Fig. 13 shows the simulation results for motor torque response for classical DTC for a reference speed of 1500 rpm. The motor is allowed to run without load torque. As observed, the transient and steady state ripple are high for classical DTC

Fig. 14 shows the simulation results for no-load stator current for classical DTC for a reference speed of 1500 rpm.

V. Conclusion

In this paper, main characteristics of field-oriented and direct torque control schemes for Induction motor drive are studied by simulation with a view to highlighting the advantages and disadvantages of each approach. From the implementation it is clear that implementation complexity is high in FOC when compared to DTC. The other objective of the paper is to give a fair comparison between FOC and DTC techniques, to allow the users to identify the more suitable solution for any application that requires torque control. Several numerical simulations have been carried out in steady state and transient operating conditions. The conclusion is that the whole performance of the two schemes is comparable. DTC might be preferred for high dynamic applications, but, on the other hand, it suffers from higher current and torque ripple.

APPENDIX A
3-PHASE INDUCTION MOTOR PARAMETERS

Rotor type: Squirrel cage, Reference frame: Stationary 4KW, 1440 rpm, 50Hz, 4 Poles, $R_s = 1.57\Omega$, $R_r = 1.21\Omega$, Ls = 0.17 H, Lr = 0.17 H, Lm = 0.165 H, J = 0.06 Kg-m2.

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