Implementation Of FOC Technique And DTC Technique For The Torque Control Of Induction Motor And Their Comparison

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Abstract—**Field-oriented control and direct torque control are becoming the industrial standards for induction motors torque control. This paper is aimed to give a contribution for a detailed comparison between the two control techniques, emphasizing advantages and disadvantages. The performance of the two control schemes is evaluated in terms of torque and current ripple, and transient response to step variations of the torque command. The analysis has been carried out on the basis of theresults obtained by numerical simulations, where secondary effects introduced by hardware implementation are not present.**

Index Terms*—D*irect field oriented control, direct torque control, discrete space vector modulation, field oriented control, pulse-width modulation.

I. INTRODUCTION

ALMOST 30 years ago, in 197 F.Blaschke [1] presented the first paper on field oriented control (FOC) for induction motors. Since that time, the technique was completely developed and today is mature from the industrial point of view. Today field oriented controlled drives are an industrial reality and are available on the market by several producers and with different solutions and performance [2] [19]. Thirteen years later, a new technique for the torque control of induction motors was developed and presented by Takahashi as direct torque control (DTC) [20]–[22], and by M. Depenbrock as direct self control (DSC) [23]–[25]. Since the beginning, the new technique was characterized by simplicity, good performance and robustness [20]–[31]. Using DTC or DSC it is possible to obtain a good dynamic control of the torque without any mechanical transducers on the machine shaft. Thus, DTC and DSC can be considered as “sensorless type” control techniques. The basic scheme of DSC is preferable in the high power range applications, where a lower inverter switching frequency can justify higher current distortion. In this paper, the attention will be mainly focused on the basic DTC scheme, which is more suitable in the small and medium power range applications.

Several papers have been published on FOC and DTC in the last 30 years, but only few of them was aimed to emphasize differences, advantages and disadvantages.

The name direct torque control is derived by the fact that, on the basis of the errors between the reference and the estimated

values of torque and flux, it is possible to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits.

Unlike FOC,DTC does not require any current regulator, coordinate transformation and PWM signals generator (as a consequence timers are not required). In spite of its simplicity, DTC allows a good torque control in steady-state and transient operating conditions to be obtained. The problem is to quantify how good the torque control is with respect to FOC. In addition, this controller is very little sensible to the parameters detuning in comparison with FOC.

On the other hand, it is well known that DTC presents some disadvantages that can be summarized in the following points:

1) difficulty to control torque and flux at very low speed;
2) high current and torque ripple;
3) variable switching frequency behaviour;
4) high noise level at low speed;
5) lack of direct current control.

Thus, on the basis of the experience of the authors, the aim of this paper is to give a fair comparison between the two techniques (FOC and DTC) in both steady-state and transient operating conditions. The comparison is useful to indicate to the users which one of the two schemes can be efficiently employed in the various applications that today require torque control.

II PRINCIPLE OF FOC.

The principle of the field oriented control (FOC) the induction motor is based on an analogy to the separately excited DC motor. In this motor flux and torque can be controlled independently. The algorithm can be implemented using simple regulator, e.g. PI-regulator.

Considering the d-q model of the induction machine in the reference frame rotating at synchronous speed ω_e The field-oriented control implies that the component of the stator current would be aligned with the rotor field and the component would be perpendicular to This can be accomplished by choosing as sped of the rotor flux and locking the phase of the reference frame system such that the rotor flux is aligned precisely with the d axis, as illustrated in Figure 1 below.

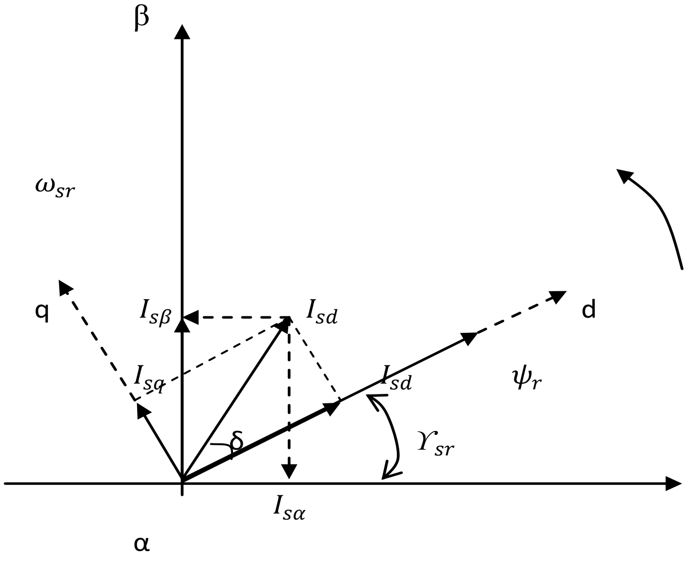

Fig.1 Phesor diagram describing the FOC scheme

From Fig.1 it can be established that

$$\psi_{dr} = 0 = \frac{d}{dt}\ \psi_{qr}$$

And $\psi_{dr} = \psi_r$

Hence the flux equation gets reduced to

$$\psi_r = \frac{L_m}{1+T_r s}(\ i_{ds})$$

And torque can be expressed as:

$$T_e = \frac{3}{2} p \frac{L_m}{L_r} (\psi_{dr}\, i_{qs} - \psi_{qr}\, i_{ds})$$

Following which the expression for T_e can be reduced to

$$T_e = \frac{3}{2}\,\mathrm{p}\,\frac{L_m}{L_r}(\ \psi_{dr}\, i_{qs})$$

$$T_e = \frac{3}{2}\,\mathrm{p}\,\frac{L_m}{L_r}\ \ i_{qs}\, L_m i_{ds}$$

$$T_e = \frac{3}{2}\, p\, \frac{{L_m}^2}{L_r}\, i_{qs}\, i_{ds}$$

Torque component   Flux
component of   current
current

Hence the analogy with the DC machine performance is clearly established, while keeping the flux constant. The electric torque T_e is proportional to the i_{qs} component of the current and flux ψ_r is proportional to the i_{ds} component of the current.

he block diagram of the direct field oriented control (DFOC) is shown in fig.2 in which the estimator or observer calculates the rotor flux angle Υ_{sr}. Inputs to the estimator or observer are stator voltages and currents.

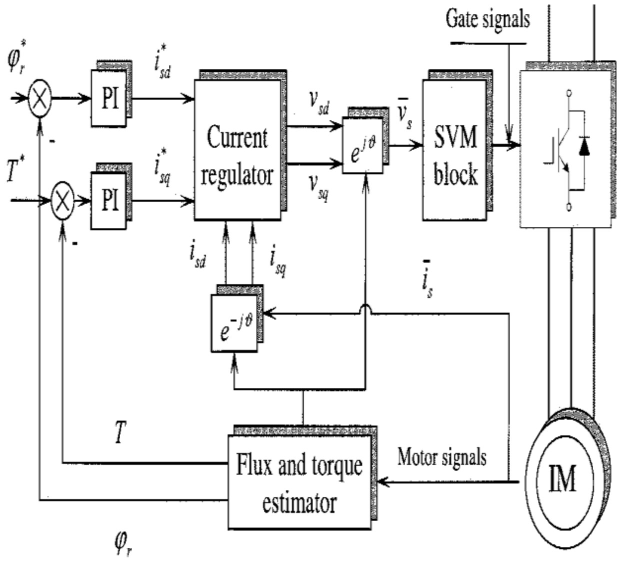

Fig.2 Basic block diagram of DFOC

* The FOC Algorithm *

1. Measure the stator phase current i_a, i_b and i_c
2. Transform these set of three phase current on to two axis system. This conversion will provide the values if i_α,and i_β from the measured values of i_a, i_b and i_c where i_α,and i_β are the time - varying quadrature current values as viewed from the stator's perspective.
3. Calculate the rotor flux and its orientation
4. Rotate the two -axis coordinate system such that it is an alignment with the rotor flux, using the transformation angle calculated at the last iteration of the control loop. This conversion provides the i_d, i_q values from i_α,and i_β
5. Flux error signal formed using flux reference and estimated flux value. A PI controller is used then to calculate the $i_d{}^*$ using the error signal. $i_q{}^*$ is generated using the reference torque value and the estimated flux value.
6. $i_d{}^*$ and $i_q{}^*$ are converted to set of three phase currents to produce $i_a{}^*, i_b{}^*$ and $i_c{}^*$
7. $i_a{}^*, i_b{}^*, i_c{}^*$ and i_a, i_b, i_c are compared using hysteresis to generate the gate signal

III. PRINCIPLE OF DTC.

The machine equations in the stator reference frame in terms of space vectors are

$$T_e = \frac{3}{2}\,\mathrm{p}\,(\psi_{dr}\, i_{qs} - \psi_{qr}\, i_{ds})$$

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr}$$

$$\psi_{ds} = L_s i_{ds} + L_m \left(\frac{\psi_{dr} - L_m i_{ds}}{L_r} \right)$$

$$\psi_{ds} = L_s i_{ds} + \frac{L_m}{L_r}\psi_{dr} - \frac{{L_m}^2}{L_r} i_{ds}$$

$$\psi_{ds} = \left(L_s - \frac{{L_m}^2}{L_r}\right) i_{ds} + \frac{L_m}{L_r}\psi_{dr}$$

$$\psi_{ds} = \left(1 - \frac{{L_m}^2}{L_r\, L_s}\right) i_{ds} + \frac{L_m}{L_r}\psi_{dr}$$

$$\psi_{ds} = 6\, L_s i_{ds} + \frac{L_m}{L_r}\psi_{dr}$$

Where the 6 is rotor leakage factor

$$6 = \left(1 - \frac{{L_m}^2}{L_r\, L_s}\right)$$

$$i_{ds} = \frac{1}{6L_s}\left(\psi_{ds} - \frac{L_m}{L_r}\psi_{dr}\right)$$

$$i_{ds} = \frac{1}{6L_s}\left(\psi_{qs} - \frac{L_m}{L_r}\psi_{qr}\right)$$

The torque equation for the induction motor is

$$T_e = \frac{3}{2} p\, (\psi_{ds} i_{qs} - \psi_{qs} i_{ds})$$

$$T_e = \frac{3}{2}\, p\, \frac{L_m}{6L_s\, L_r}\, [\psi_{qs}\psi_{dr} - \psi_{ds}\psi_{qr})$$

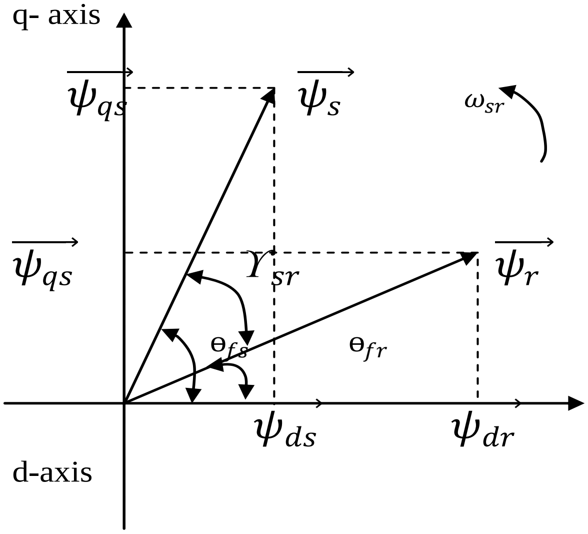

Fig.3 vector diagram of stator and rotor flux

From the Fig.3 vector diagram following equations are written.

$$\psi_{ds} = \psi_s \cos \theta_{fs}$$

$$\psi_{qs} = \psi_s \sin \theta_{fs}$$

$$\psi_{dr} = \psi_r \cos \theta_{fr}$$

$$\psi_{qr} = \psi_r \sin \theta_{fr}$$

$$T_e = \frac{3}{2}\,\mathrm{p}\,\frac{L_m}{6L_s\, L_r}\,[\psi_s\psi_r \sin\theta_{fs} \cos\theta_{fr} - \psi_s\,\psi_r \cos\theta_{fs} \sin\theta_{fr}\,]$$

$$T_e = \frac{3}{2}\,\mathrm{p}\,\frac{L_m}{6L_s\, L_r}\,\psi_s\,\psi_r \sin(\theta_{fs} - \theta_{fr})$$

$$T_e = \mathrm{k}\,\psi_s\,\psi_r \sin \Upsilon_{sr}$$

Where **k** is constant

$$k = \frac{3}{2} p \frac{L_m}{6L_s L_r}.$$

the basic block diagram for the DTC of induction motor is shown in Fig.4.

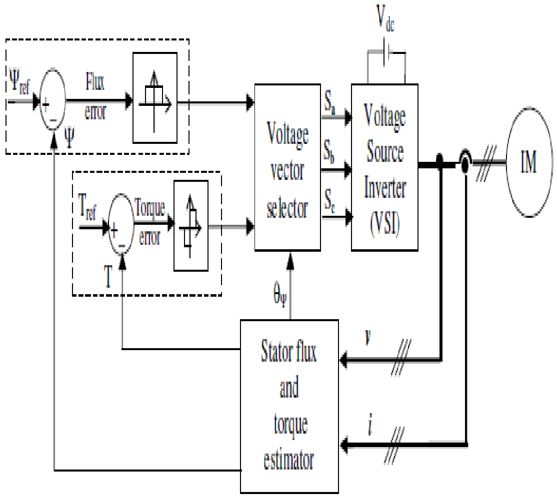

Fig.4 basic block diagram of DTC

The error between the estimated torque T and reference torque T* is output of the three level hysteresis comparator

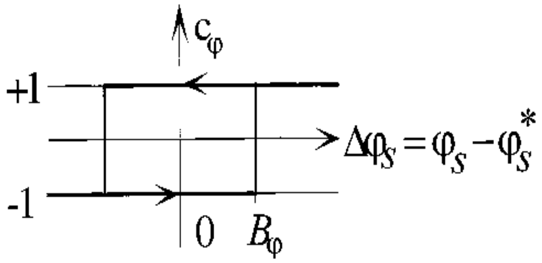

Fig.5 Flux hysteresis comparator.

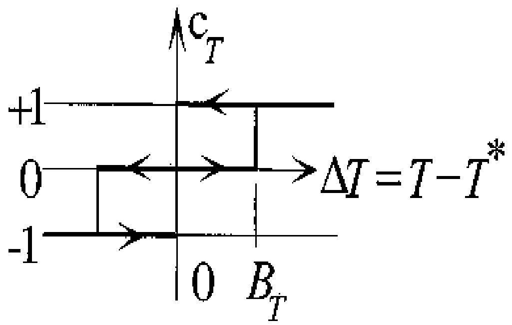

Fig.6 Torque hysteresis comparator.

Whereas the error between the stator flux magnitude ψ_s and reference flux magnitude $\psi_s *$ is the input of the two level hysteresis comparator. Fig. 5 & 6 illustrates the flux and torque comparator respectively.

The selection of appropriate voltage vector is based on is based on switching table given in table-1. The input quantities are the stator flux sector and the output of two hysteresis comparator. Assuming the flux stator flux vector laying in sector 1 of the d-q plane. The vectors used by the DTC technique is given in the Fig.7.

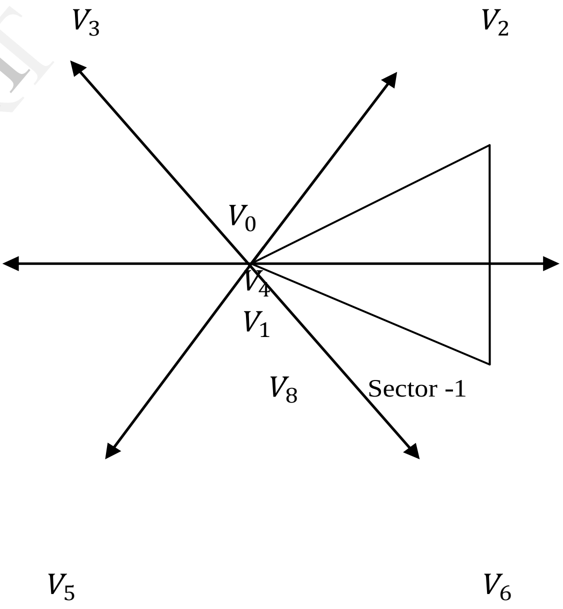

Fig.7 voltage vectors utilised in basic DTC scheme when the stator flux is in sector – 1.

TABLE-1

Basic switching table

Sector / status		1	2	3	4	5	6
$d\psi = 1$	dm= 1	V_2	V_3	V_4	V_5	V_6	V_7
	dm= 0	V_7	V_0	V_7	V_0	V_7	V_0
	dm= -1	V_6	V_1	V_2	V_3	V_4	V_5
$d\psi = 0$	dm = 1	V_3	V_4	V_5	V_6	V_1	V_2
	dm = 0	V_0	V_7	V_0	V_7	V_6	V_7
	dm= -1	V_5	V_6	V_1	V_2	V_3	V_4

This simple approach allow a quick torque response to be achieved, but the steady state performance is characterised by undesired ripple in current, flux & torque. This behaviour is mainly due to the absence of information about the torque and the rotor speed values in voltage vector selection algorithm.

The DTC algorithm

1. Measure the values of stator currents i.e. $i_a, i_b,\ i_c$ and v_a, v_b, v_c
2. Transform these set of three phase current on to two axis system. This conversion will provide the values if i_α,and i_β from the measured values of i_a, i_b and i_c where i_α,and i_β are the time - varying quadrature current values as viewed from the stator's perspective. Similarly calculate the voltages
3. Rotate the two -axis coordinate system such that it is an alignment with the rotor flux, using the transformation angle calculated at the last iteration of the control loop. This conversion provides the i_d, i_q values from i_α,and i_β and values $v_d,\ v_q$ from the v_α & v_β.
4. Using these values calculate the values of torque, flux & angle i.e. θ_{fs}
5. Calculate the reference values of the torque* and flux* from the actual speed of the rotor.
6. Give actual values and reference values of torque and flux to the hysteresis controller. And the angle is given as input to the sector selector. Which finds the sector in which the flux is laying.
7. The hysteresis controller is generates the appropriate gate signals as per the switching table shown in table no.1

IV. SIMULATION RESULTS AND ANALYSIS.

Fig.8 & Fig.9 shows the simulink model of the FOC scheme and the DTC respectively. The torque response , speed response and the stator currents of the induction motor are shown in Fig.9 & 10 for the FOC and DTC respectively. In both the cases the load torque is initially 10 Nm. & 30 Nm. At 1 sec is applied. And reference speed is set to 500rpm, &1000rpm at 0sec & 1sec respectively.

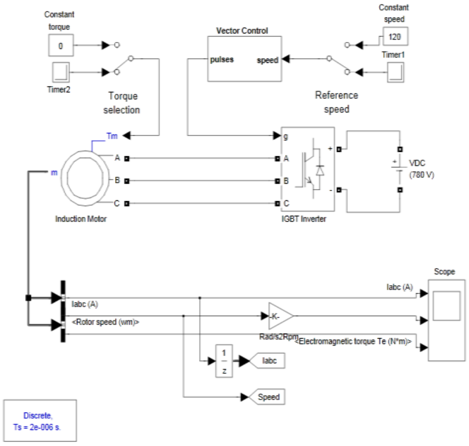

Fig.8 Matlab/Simulation of FOC scheme

In the DTC scheme direct control of the stator current is not present and this may determine over currents when step variation of torque and flux are applied to the input command. With reference to the torque an indirect torque current control can be obtained introducing a limit to the maximum torque value. With reference to the stator flux it can be noted command causes large variation of

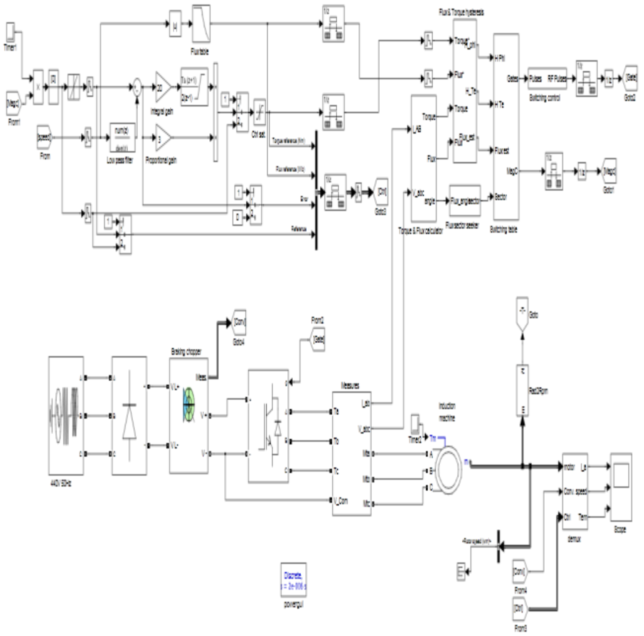

Fig. 9 Matlab/Simulation of DTC scheme.

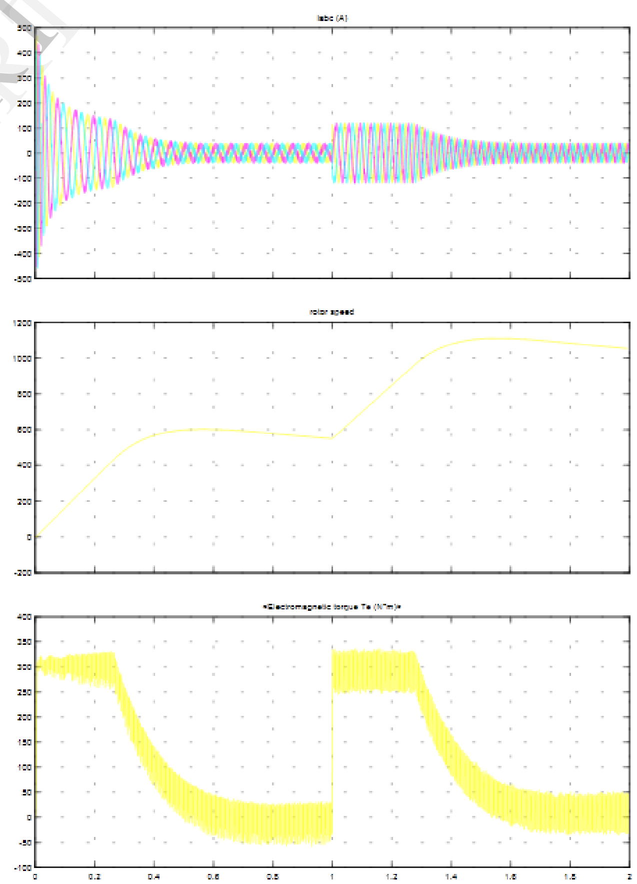

Fig8. stator currents (Iabc), rotor speed, and electromagnetic torque response of vector control scheme.

the stator current. It is well known that the basic DTC scheme is affected by undesirable phenomena at low speed. In these operating conditions the control system selects many times zero votage vectors, determining a reduction of flux level owing to the effects of stator resistance voltage drop. Fig.10 &11 shows the stator flux trajectory for DTC scheme & FOC scheme respectively

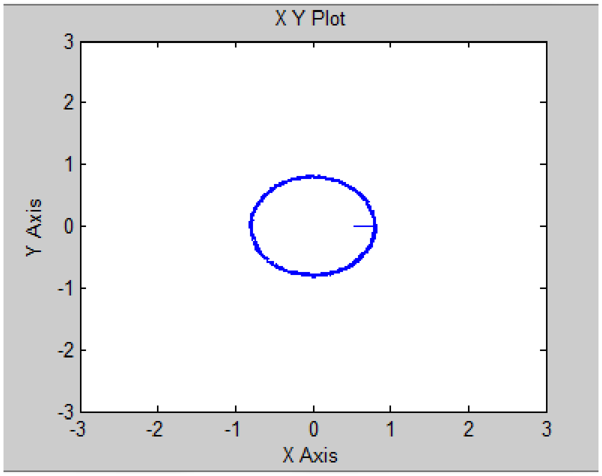

Fig.10 stator flux trajectory of DTC scheme

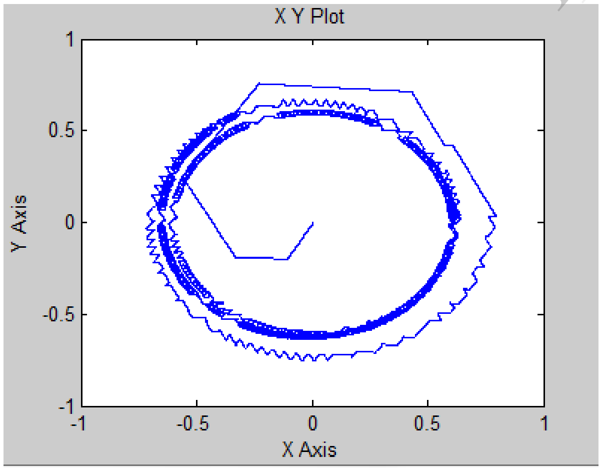

Fig.11 stator flux trajectory of FOC scheme.

V Conclusion And future prospects.

The aim of the paper was, implementation of DTC & FOC schemes of control for the induction motor and their fair comparison by analysing the outputs of both the techniques, to allow the user to indentify the more suitable solution for any application that requires torque control

From the analysis can be concluded that the DTC scheme has the upper hand as compare to the FOC except that it has the more toque ripples, and the large variable switching frequency causes the more switching losses and the ripple which can be reduced by using the space vector pulse width modulation direct torque control (SVPWMDTC) many researches are going on the field to implement the DTC with minimum ripples in the torque. Also by designing the sliding mode

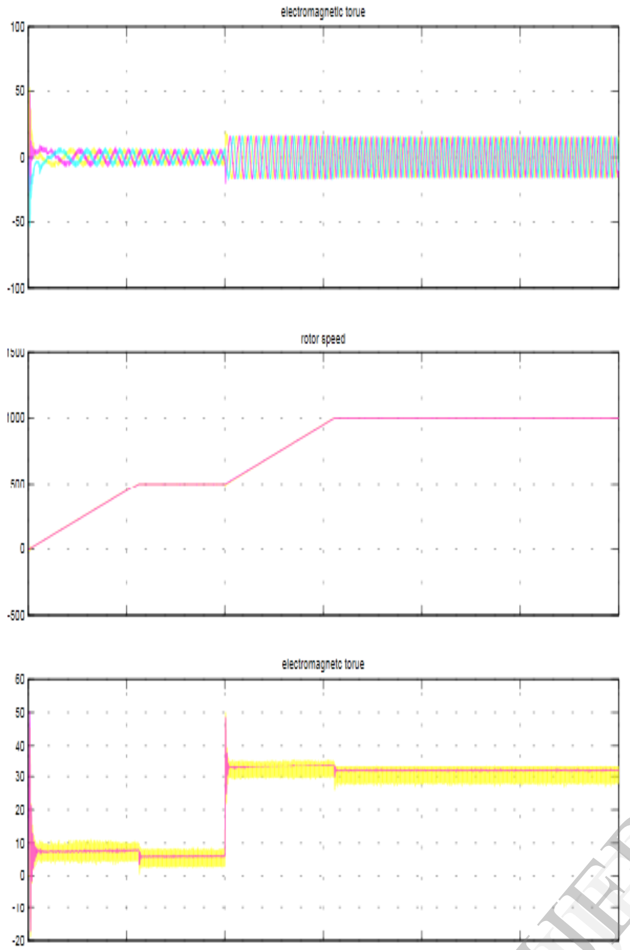

Fig.9 stator currents (Iabc), rotor speed, and electromagnetic torque response of DTC technique scheme.

controller we can further reduce the ripples from the output hence the output torque variation will be more perfect and smooth.

Appendix

The test macine used in the MATLAB/simulation is 3phase, 50HZ induction machine having the following parameter

Power output	5HP
Rated Voltage	350V
Stator resistance	1.115Ω
Stator inductance	0.005974H
Rotor resistance	1.083 Ω
Rotor inductance	0.005974H
Mutual inductance	0.2037H
Pole pair	2
Inertia	0.002

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