

# QUICK DYNAMIC TORQUE CONTROL IN DTC-HYSTERESIS-BASED INDUCTION MOTOR BY USING NEW OPTIMIZED SWITCHING STRATEGY

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## ABSTRACT

Induction machines are widely employed in industries due to their rugged structure, high maintainability and economy than DC motors. There has been constant development in the induction motor drive system and their implementation in industrial applications. The improvement of switching speed of power electronic devices has enabled control techniques which possess high switching frequency and feasibility of high efficiency drive systems. In this pretext, Direct Torque Control (DTC) was introduced to obtain quick and better dynamic torque response. The DTC scheme in its basic configuration comprises torque and flux estimator DTC controller, stator voltage vector selector and voltage source inverter. Direct Torque Control of induction motor has increasingly become the best alternative to Field- Oriented Control methods. The performance of an induction motor under the classical Direct Torque Control method and improved scheme have been studied and confirmed by simulation using MATLAB.

**Keywords:** Direct Torque Control (DTC), Dynamic Over-modulation, Hysteresis Controller, Induction Motor, Torque Controller.

## INTRODUCTION

Industrial loads require operation at wide range of speeds. Such loads are generally termed as variable speed drives. These drives demand precise adjustment of speed in a steeples manner over the complete speed range required. The loads may be constant torque or a function of speed. These loads are driven by hydraulic, pneumatic or electric motors. An industrial drive has some special features when driven by electric motors. Induction machines have provided the most common form of electromechanical drive for industrial, commercial and domestic applications that can operate at essentially constant speed. Induction machines have simpler and more rugged structure, higher maintainability and economy than dc motors. They are also robust and immune to heavy loading. The possible forms of drive motors are dc drives, ac drives. DC motors are versatile for the purpose of speed control but they suffer from the disadvantage imposed by the commentator. On the other hand ac drives are viable competitors with the advent of thruster power converter technology. The evolution of ac variable speed drive technology has been partly driven by the desire to emulate the performance of dc drive such as fast torque response and speed accuracy, while utilising the advantages offered by standard ac motor. The Field Oriented Control (FOC) and the Direct Torque Control (DTC) are two types of drives employed for high performance applications. Direct Torque Control was introduced in Japan by Takahashi (1984) and Depenbrock (1985). Vector controlled induction motors are employed in high performance drives having precise speed control and good static as well as dynamic response. Direct Torque Controlled drives have increasingly become the best alternative to Field-Oriented Control methods [10], [2]. Modern control methods use state space techniques. The methods of stabilizing the drives and improvement in their transient responses have been realized by modern power electronic devices [3]. The block diagram of Direct Torque Control for an induction motor is as shown in Fig. 1. The

DTC scheme comprises torque and flux estimator, hysteresis controllers for flux and torque and a switching table.

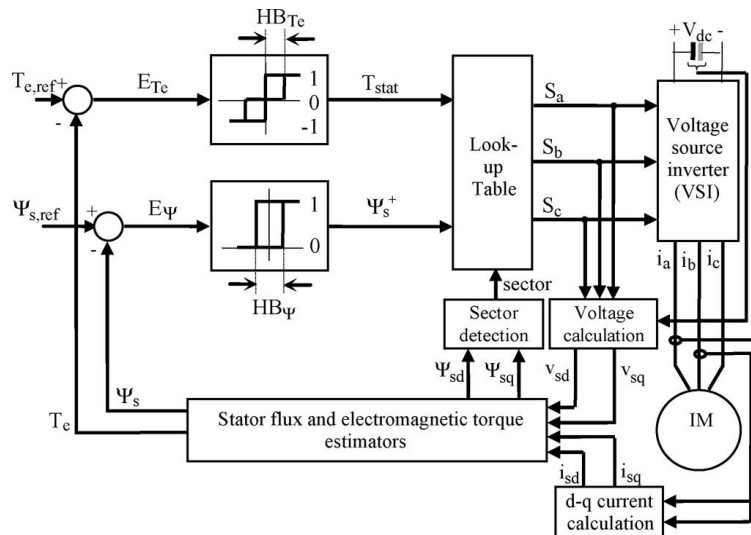


Fig. 1 Structure of basic DTC-hysteresis-based induction machine

## INDUCTION MOTOR MODEL

The main objective of DTC is to control the induction motor. The per-phase equivalent circuit of an induction motor is valid only in steady-state condition. In an adjustable speed drive like the DTC drive, the machine normally constitutes an element within a feedback loop and hence its transient behavior has to be taken into consideration [4]. The induction motor can be considered to be a transformer with short circuited and moving secondary. The coupling coefficients between the stator and rotor phases change continuously in the course of rotation of rotor [6], [5]. Hence the machine model can be described by differential equations with time varying mutual inductances.

## DIRECT TORQUE CONTROL CONCEPT

In recent years “induction motor control techniques” have been the field of interest of many researchers to find out different solutions for induction motor control having the features of precise and quick torque response, and reduction of the complexity of field oriented control [3]-[7]. The Direct torque control (DTC) technique has been recognized as the simple and viable solution to achieve this requirements. DTC is one of the most excellent and efficient control strategies of induction motor. This technique is based on decoupled control of torque and stator flux and today it is one of the most actively researched control techniques where the aim is to control effectively the torque and flux.

## CONVENTIONAL DTC SCHEME

The conventional DTC scheme is a closed loop control scheme, the important elements of the control structure being: the power supply circuit, a three phase voltage source inverter, the induction motor, the speed controller to generate the torque command and the DTC controller. The DTC controller again consists of torque and flux estimation block, two hysteresis controllers and sector selection block, the output of the DTC controller is the gating pulses for the inverter.

The DTC scheme does not require coordinate transformation as all the control procedures are carried out in stationary frame of reference. So this scheme does not suffer from parameter variations to the extent that other control techniques do. Also there is no feedback current control loop due to which the control actions do not suffer from the delays inherent in the current controllers, no pulse width modulator, no PI controllers, and no rotor speed or position Sensor So it is a sensorless control technique which operates the motor

without requiring a shaft mounted mechanical sensor. Here on-line torque and flux estimators are used for closing the loop. Here the torque and stator flux are controlled directly by using hysteresis comparators. Fig.1 shows the basic block diagram of conventional DTC scheme [8]-[10].

## PRINCIPLE OF DTC SCHEME

The basic principle of DTC is to directly select stator voltage vectors according to the torque and flux errors which are the differences between the references of torque and stator flux linkage and their actual values. The governing equation for torque for this scheme is due to the interaction of stator and rotor fields. Torque and stator flux linkage are computed from measured motor terminal quantities i.e. stator voltages and current. An optimal voltage vector for the switching of VSI is selected among the six nonzero voltage vectors and two zero voltage vectors by the hysteresis control of stator flux and torque.

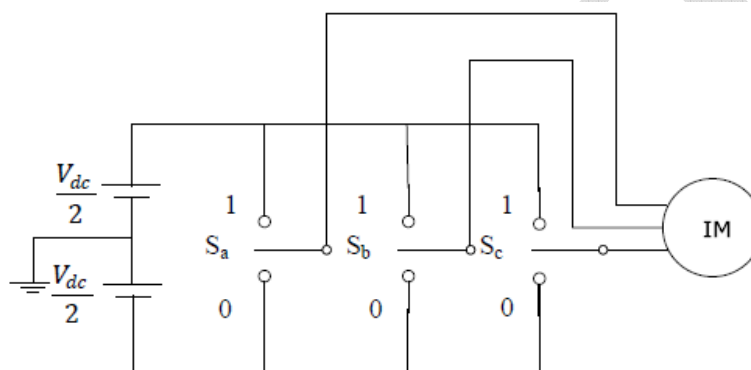


Fig. 2 Simplified 3- $\phi$  VSI

A three-phase VSI has eight possible combinations of six switching devices which is shown in fig.2. The six switches have a well defined state: ON or OFF in each configuration. So all the possible configurations can be identified with three bits (Sa, Sb, Sc), one for each inverter leg [17]. The bit is set to 1 if the top switch is closed and to 0 when the bottom switch is closed. In order to prevent short circuit of the supply, the state of the upper switch is always opposite to that of the lower one. The stator voltage space vector is,

$$\vec{V}_s = \frac{2}{3} E (S_a + e^{j\frac{2\pi}{3}} S_b + e^{j\frac{4\pi}{3}} S_c)$$

## DIRECT FLUX CONTROL

In stationary reference frame the stator flux equation can be written as:

$$\dot{\psi}_s = \int (\vec{v}_s - \vec{i}_s R_s) dt$$

If the stator resistance drop is neglected for simplicity, the stator flux varies along the direction of applied voltage vector and the equation will be reduced to

$$\Delta \vec{\psi}_s = \vec{V}_s \Delta t$$

Which means, by applying stator voltage vector  $\vec{V}_s$  for a time increment  $\Delta t$ ,  $\psi_s$  can be changed incrementally. The command value of the stator flux vector  $\psi_s^*$  follows a circular trajectory, the plane of stator flux is divided into six sectors as shown in fig.3. Each sector has a different set of voltage vector to increase or decrease the stator flux. The command flux vector rotates in anticlockwise direction in a circular path and the actual stator flux vector  $\psi_s$  tracks the command flux in a zigzag path but constrained to the hysteresis band which is shown in fig.3.

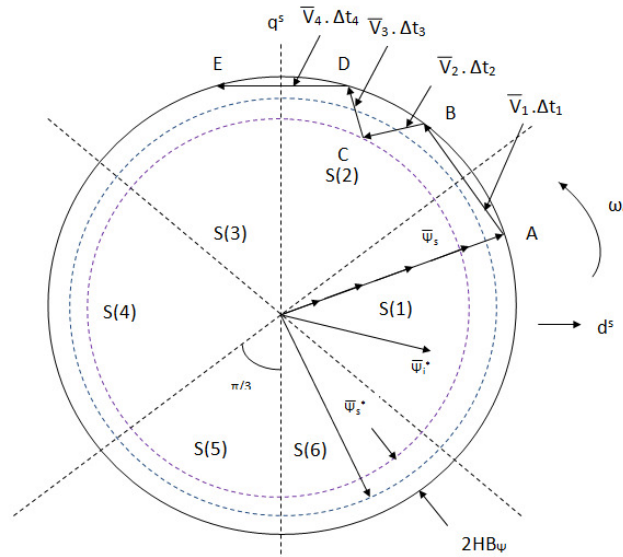


Fig. 3 Circular Trajectory of stator flux

In general the active forward voltage vectors ( $V_{s,k+1}$  and  $V_{s,k+2}$ ) are applied to increase or decrease the stator flux respectively when the stator flux lies in sector  $k$ . The radial voltage vectors ( $V_{s,k}$  and  $V_{s,k+3}$ ) which quickly affect the flux are generally avoided. The active reverse voltage vectors ( $V_{s,k-1}$  and  $V_{s,k-2}$ ) are used to increase or decrease the stator flux in reverse direction.

The stator flux vector change due to stator voltage vector is quick whereas change rotor flux is sluggish because of its large time constant  $T_r$ . That is why  $\Psi_{\square_s}$  movement is jerky and  $\Psi_{r\square}$  moves uniformly at frequency  $\omega_e$  as it is more filtered. However the average speed of both remains the same in steady state condition.

## DIRECT TORQUE CONTROL

The electromagnetic torque produced due to interaction of stator and rotor flux is given by the following equation:

$$T_e = \frac{3}{2} \left( \frac{P}{2} \right) \frac{L_m}{L'_s L_r} \overline{\psi_s} * \overline{\psi_r} = \frac{3}{2} \left( \frac{P}{2} \right) \frac{L_m}{L'_s L_r} \psi_s \psi_r \sin \gamma$$

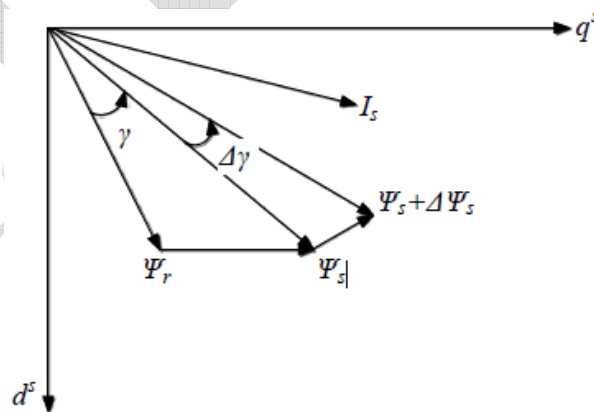


Fig. 4 Stator flux, rotor flux and stator current vectors in  $ds$ - $qs$  reference plane

From the above it is clear that torque varies directly as angle between stator flux and rotor flux i.e.  $\gamma$ . So in order to obtain high dynamic performance it is required to vary  $\gamma$  quickly. Assuming the rotor is rotating in anticlockwise direction continuously and stator flux lies in sector  $k$ , the active forward voltage vectors ( $V_{s,k+1}$  and  $V_{s,k+2}$ ) are applied to increase  $\gamma$  so as the torque  $T_e$ . The radial voltage vectors ( $V_{s,k}$  and  $V_{s,k+3}$ ) are used to

decrease  $\gamma$  and  $T_e$ . By applying the reverse active voltage vectors ( $V_{s,k-1}$  and  $V_{s,k-2}$ ) torque can be decreased rapidly. The two zero voltage vectors ( $V_{s,0}$  and  $V_{s,7}$ ) are applied to maintain the flux constant ideally and to decrease the torque slightly.

## SWITCHING SELECTION

A high performance torque control can be established due to the decoupled control of stator flux and torque in DTC. Optimum switching vector selection table given by table 3.1 shows the optimum selection of the switching vectors in all sectors of the stator flux plane. This table is based on the value of stator flux error status, torque error status and orientation of stator flux for counterclockwise rotation of the shaft [8].

Table 1 Lookup Table (voltage vector selector)

Stator Flux error status	Torque error status	Sector I	Sector II	Sector III	Sector IV	Sector V	Sector VI
1	1	$V_2$ (100)	$V_3$ (110)	$V_4$ (010)	$V_5$ (011)	$V_6$ (001)	$V_1$ (101)
	0	$V_0$	$V_7$ (111)	$V_0$ (000)	$V_7$ (111)	$V_0$ (000)	$V_7$ (111)
	-1	$V_6$ (001)	$V_1$ (101)	$V_2$ (100)	$V_3$ (110)	$V_4$ (010)	$V_5$ (011)
0	1	$V_3$ (110)	$V_4$ (010)	$V_5$ (011)	$V_6$ (001)	$V_1$ (101)	$V_2$ (100)
	0	$V_7$ (111)	$V_0$ (000)	$V_7$ (111)	$V_0$ (000)	$V_7$ (111)	$V_0$ (000)
	-1	$V_5$ (011)	$V_6$ (001)	$V_1$ (101)	$V_2$ (100)	$V_3$ (110)	$V_4$ (010)

## STATOR FLUX ESTIMATION

For exact calculation of stator flux and torque errors, an accurate estimator of stator flux is necessary. There are commonly used methods of estimation of flux namely stator voltage model and current model.

## HYSTERESIS CONTROLLER

DTC of induction motor drives requires two hysteresis controllers. The drive performance is influenced by the width of the hysteresis bands in terms of flux and torque ripples, current harmonics and switching frequency of power electronics devices. Current distortion is reduced by small flux hysteresis band and torque ripple is reduced by small torque hysteresis bands. In each sampling time, the switching state of the inverter is updated. The inverter state remains constant, until the output states of the hysteresis controller change within a sampling interval. If the hysteresis band is fixed, the switching frequency totally depends on the rate of change of torque and flux.

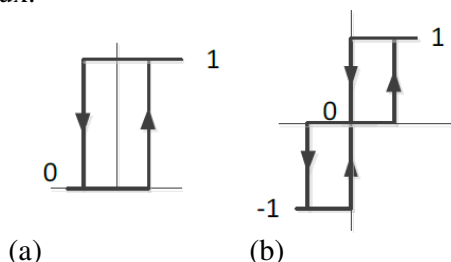


Fig.5 Hysteresis Band (a) the stator flux, (b) electromagnetic torque

## PROPOSED DYNAMIC TORQUE CONTROL

In the proposed dynamic over modulation method, the most optimized voltage vector that produces the largest tangential to the circular flux locus is switched and held (instead of selecting two active voltage vectors) during torque dynamic to achieve the fastest dynamic torque control. As discussed in the previous section, if sector  $k$  is considered, this would be vector  $\mathbf{v}_{k+1}$  in subsector (i) and vector  $\mathbf{v}_{k+2}$  in subsector (ii). Fig. 6 shows the structure of DTC-hysteresis-based induction machine with the proposed modification of flux error status.

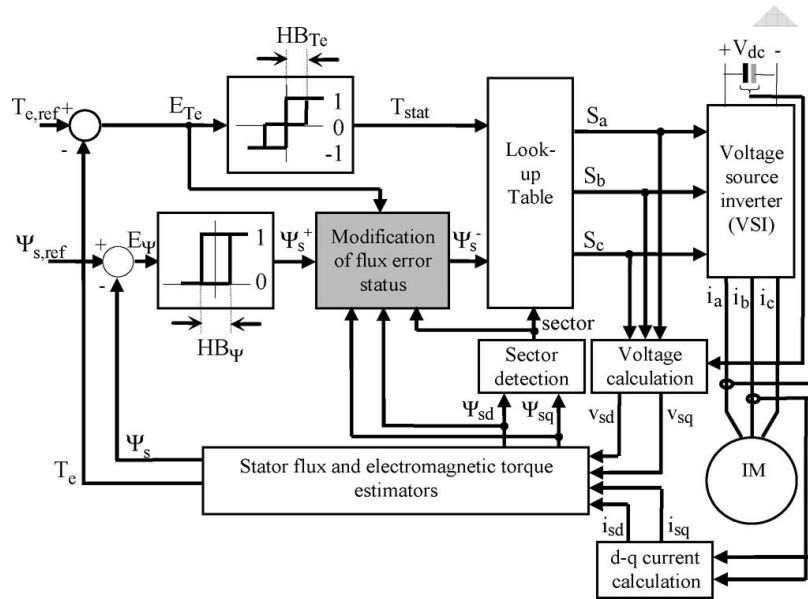


Fig. 6 Structure of DTC-hysteresis-based induction machine with the proposed Modification of flux error status block

Notice that all components of the DTC-hysteresis-based scheme are retained, except for the inclusion of the “modification of flux error status” block which is responsible to perform the dynamic over modulation mode. The selection of the optimized voltage vector to give the fastest torque response can be simply done by modifying the flux error status ( $\psi^+$ ) to a new flux status ( $\psi^-$ ) before it is being fed to the lookup table. The “modification of flux error status” block, and, hence, the proposed dynamic over modulation, is activated when the torque error  $E_{Tc}$  is greater than twice of the hysteresis band of torque controller  $HB_{Tc}$ . When the “modification of flux error status” block is activated, the output of this block  $\psi_s^-$  depends on the position of the flux position within a sector. If it is in subsector (i)  $\psi_s^- = 0$ , hence  $\mathbf{v}_{k+1}$  is selected, and if it is in subsector (ii)  $\psi_s^- = 1$ ,  $\mathbf{v}_{k+2}$  is selected. The border of the sectors and subsectors can be easily calculated using the threshold values of  $\psi_{s,q}^s$  denoted as  $\psi_{sq,1}$  and  $\psi_{sq,2}$  which can be calculated as

$$\psi_{sq,1} = \psi_{s,i}^s \tan(\pi/6)$$

$$\psi_{sq,2} = \psi_{s,i}^s \tan(\pi/3)$$

## SIMULATION MODEL AND RESULTS

To study on the effectiveness of the proposed dynamic over modulation method, a simulation of the DTC-hysteresis-based induction motor drive is performed using a Matlab/Simulink simulation package. A 1.5-kW four pole squirrel-cage induction motor is used for simulation. The simulation results are carried out for conventional and modified DTC of induction machine.

**SIMULATION MODEL OF DTC:**

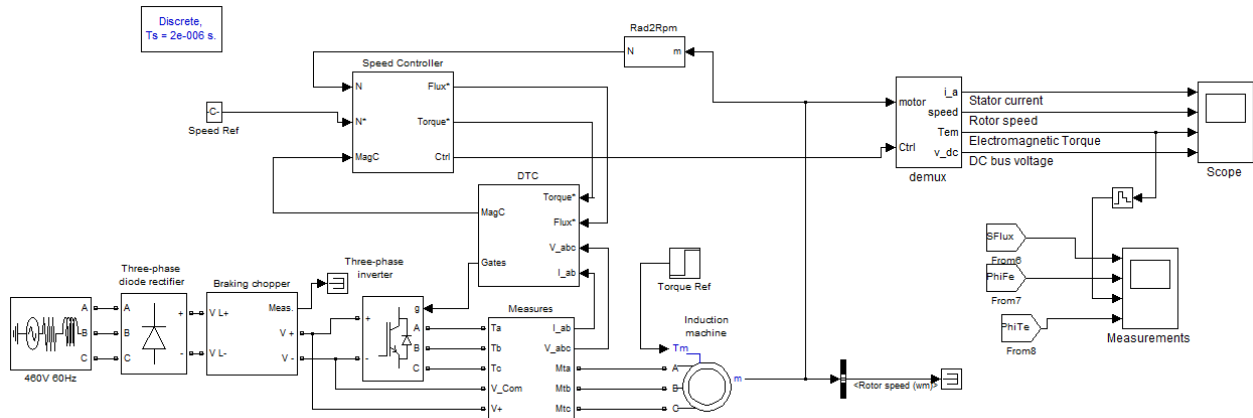
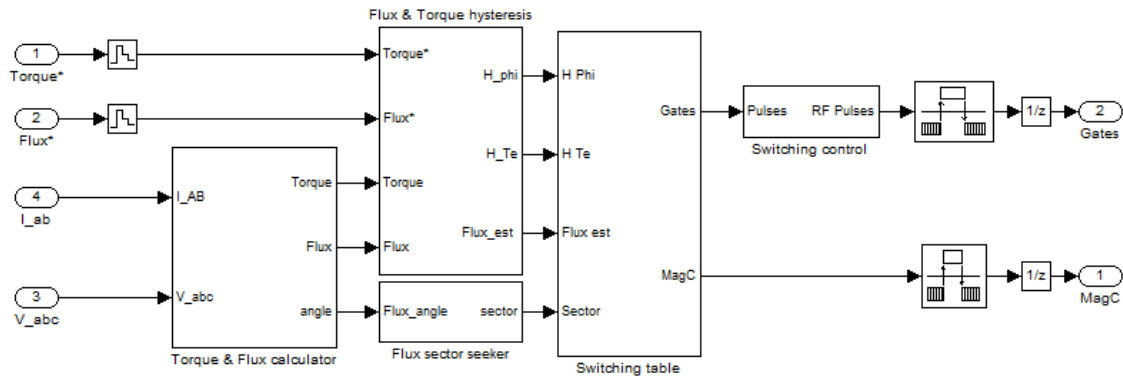
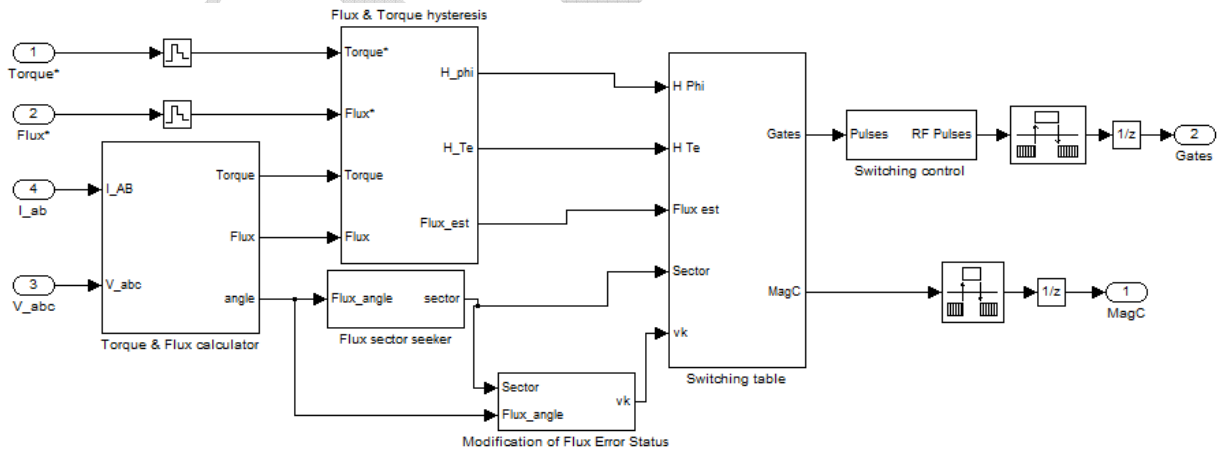


Fig.7. Simulation model of DTC

**1. DTC Block for conventional Method**



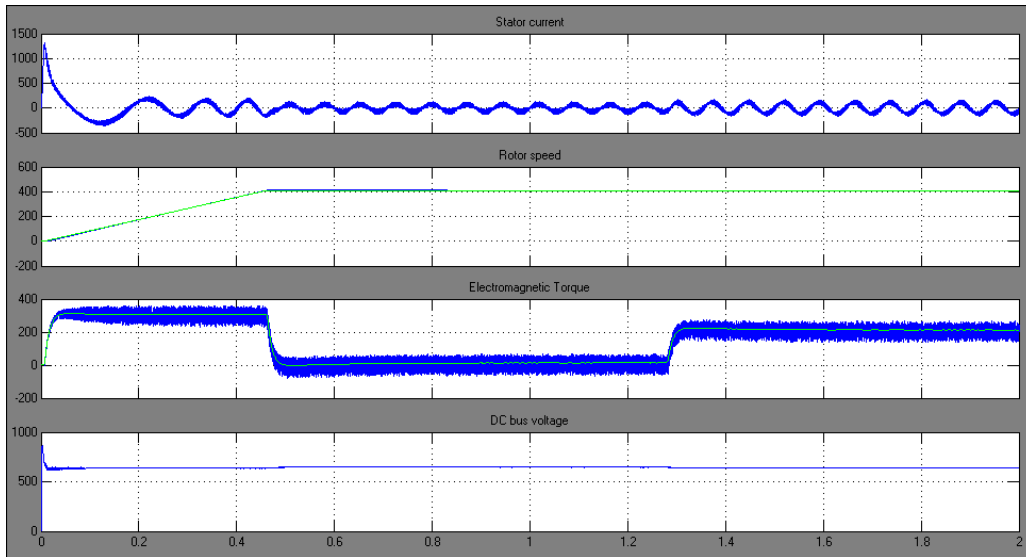
**2. DTC Block for Modified Method**



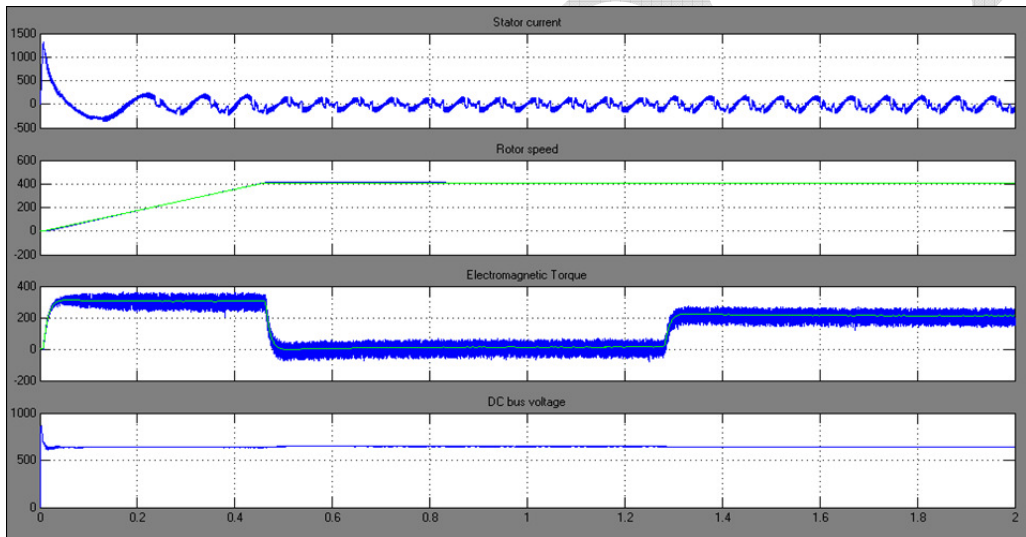
**SIMULATION RESULTS:**

Simulation results with conventional and Modified DTC are as shown below:

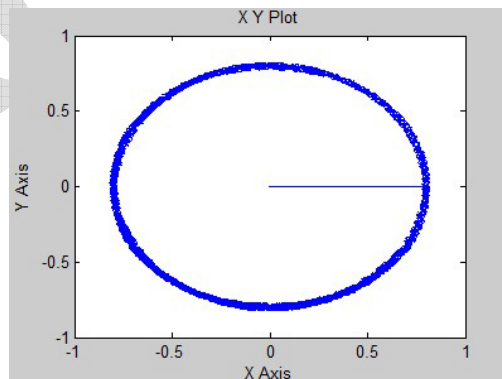
**Simulation Results of Conventional DTC:**



**Simulation Results of Modified DTC:**

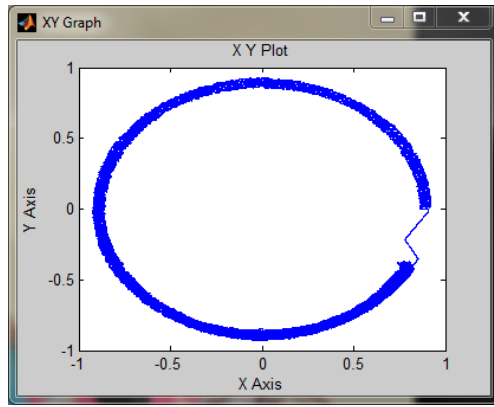


**Stator Flux Locus of Conventional DTC:**

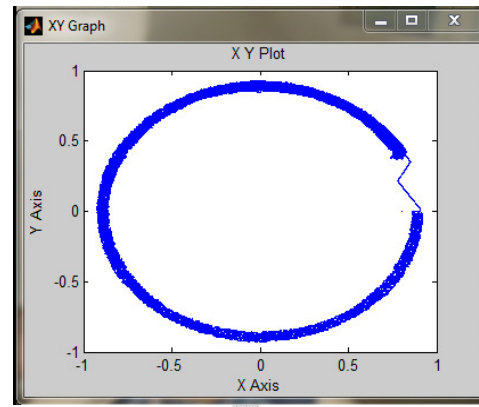


**Flux Loci for All Six Sectors with modified Method:**

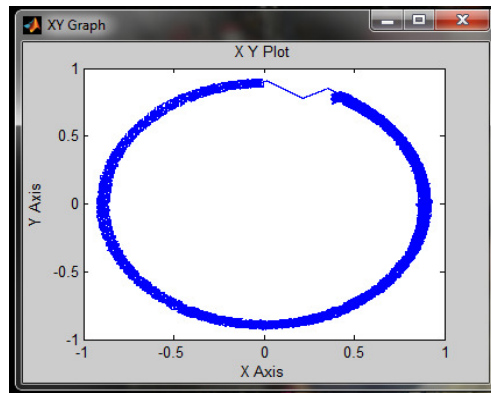




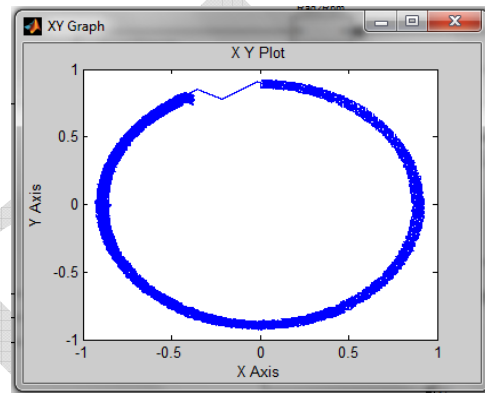
(a)



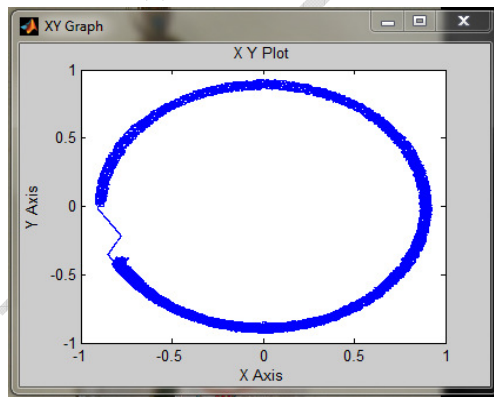
(b)



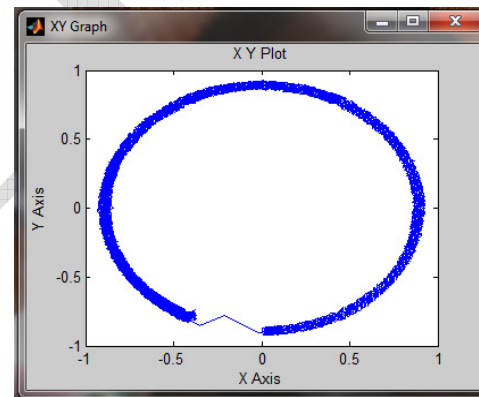
(c)



(d)



(e)



(f)

## CONCLUSION

For any IM drives, direct torque control is one of the best controllers proposed so far. It allows decoupled control of motor stator flux and electromagnetic torque. From the analysis it is proved that, this strategy of IM control is simpler to implement than other vector control methods as it does not require pulse width modulator and co-ordinate transformations.

The estimation accuracy of stator flux is very much essential which mostly depends on stator resistance because an error in stator flux estimation will affect the behavior of both torque and flux control loops. The torque and current ripple can be minimized by employing space vector modulation technique. A new strategy is introduced further to get quick response by introducing one “modified flux error block” and proved by MATLAB/SIMULINK model.

An optimized voltage vector that produces the largest tangential to the circular flux locus is switched and held so that a fast rate of change of angle  $\Delta\delta sr$  is achieved. The selection of the optimized voltage vector is simply obtained by modifying the flux error status before it is being fed to the lookup table. The main benefit of the proposed method is its simplicity and, at the same time, be able to produce the fastest dynamic torque response with a six-step mode.

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