Scientific Journal of Impact Factor(SJIF): 3.134
e-ISSN(O): 2348-4470
p-ISSN(P): 2348-6406

International Journal of Advance Engineering and Research Development

Volume 2, Issue 5, May -2015

Improved Direct Torque Control Strategies for Low Speed Range Operation of Induction Motor Drives

Aboti Ashish N.[1], Patel Tejas I[2], Pritesh Mankad R[3]

[1] *Electrical Engineering Department, HJD-ITER Kera-Kutch*
[2] *Electrical Engineering Department, HJD-ITER Kera-Kutch*
[3] *Electrical Engineering Department, HJD-ITER Kera-Kutch*

Abstract — *Induction motors are the starting point to design an electrical drive system which is widely used in many industrial applications. In modern control theory, different mathematical models describe induction motor according to the employed control methods. The direct torque control (DTC) scheme being one of the most recent steps in this direction. This scheme provides excellent properties of regulation without rotational speed feedback. In this control scheme the electromagnetic torque and stator flux magnitude are estimated with only stator voltages and currents and this estimation does not depend on motor parameters except for the stator resistance. Literature review has been done to study the recent improvements in DTC scheme especially in low speed range operation to overcome the torque ripple problem.*

The conventional direct torque controlled scheme suffers from great torque ripple due to fast response of torque in low speed. The motor speed is an important parameter which effects on the motor torque ripple in low speed, when applying a forward nonzero voltage vector causes to jump up of motor torque and this leads to a positive ripple in torque response. so we have to improve in look up table to reducing the torque ripple especially in low speed range. In thesis Simulation of conventional DTC scheme and Modified DTC scheme is described. In modified DTC scheme use the 12 sector method and 5 level hysteresis band controller.

Keywords*- Introduction, Direct torque control, 12 sector methodology, Simulation Results*

I. INTRODUCTION

Scalar control based on relationships valid in steady state, only magnitude and frequency of voltage, current and flux linkage space vectors are controlled, disregards the coupling effect in the machine. In this control, the motor is fed with variable frequency signals generated by the PWM control from an inverter using the feature rich PIC micro microcontroller. Here, the V/f ratio is maintained constant in order to get constant torque over the entire operating range. Since only magnitudes of the input variables – frequency and voltage – are controlled, this is known as "scalar control

Vector control based on relations valid in dynamics state, not only magnitude and frequency but also instantaneous position of voltage, current and flux linkage space vector are controlled. The most popular vector control methods are the Field oriented control (FOC) and DTC. Scalar controlled drives give somewhat inferior performance, but easy to implement. Their importance has been diminished recently because of the superior performance of vector controlled drives which is demanded in many applications

DTC is a simple control technique which does not require coordinate transformation, PI regulators, and Pulse width modulator and position encoders .This technique results in direct and independent control of motor torque and flux by selecting optimum inverter switching modes. The electromagnetic torque and stator flux are calculated from the primary motor inputs e.g. stator voltages and currents. The optimum voltage vector selection for the inverter is made so as to restrict the torque and flux errors within the hysteresis bands. The advantages of this control technique are quick torque response in transient operation and improvement in the steady state efficiency.

II. DIRECT TORQUE CONTROL STRATEGIES

The direct torque controlled technique is one of the best control technique is simple and very efficient, reliable control of induction motor drive [5]. In the direct torque control we have to direct change the torque and flux hence it is known that decoupled control, also known as advance scalar control.

The conventional direct control scheme is basically closed loop control scheme shown in fig 1 because rotor speed is always measured. The elements of conventional direct torque scheme are: 1) Power supply 2) 3-Ø voltage source inverter 3) induction motor 4) speed controller 5) DTC controller sub system 6) hysteresis band controller 7) switching table or lookup table. The output of DTC controller scheme is form of getting pulse which fed to voltage source inverter from switching table.

The working of direct torque control is mainly related to torque and flux error, from the torque and flux error we have select the voltage vector. this error is difference between the reference value of flux and torque with actual value of torque and flux, stator voltage and currents are measured and find the torque and flux, from this quantities select the proper voltage vector of voltage source inverter, when we selected voltage vector at that time mainly two type of voltage vector 1.non zero voltage vector 2.zero voltage vector from the hysteresis band control of stator flux and torque.

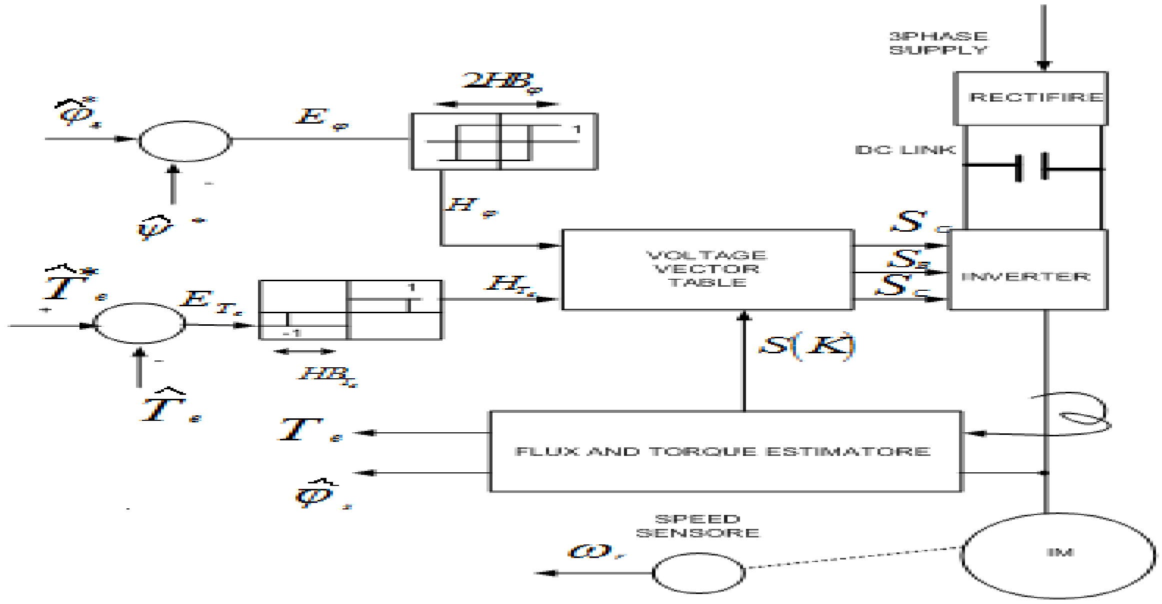

Figure 1. Block diagram of conventional DTC scheme For IM drives

A. Direct Flux Control: When stator flux equation write in stationary reference frame at a time neglected the stator resistance for simplicity hence equation reduced. when applied voltage vector at time the change in stator flux.in figure 3.3 shows that flux rotate in circular trajectory in six sectors. In all the sectors we have to increase and decreased flux according to applied voltage vector. Fig3.3 shown the command flux vector is rotate in anticlockwise and actual flux vector is rotate according to the command flux vector. This command flux vector is in zig-zag pattern within the hysteresis band.

$$\Psi d_s^s = \int (V^s d_s - i^s d_s R_s) d_t \qquad \text{……………..2.1}$$

When we have increase and decreased in stator flux in forward direction at sector k hence applied forward voltage vector $(V_{s,k+1} and\ V_{s,k+2})$. the mostly $(V_{s,k} and\ V_{s,k+3})$ is affect in flux but avoided. When we have increase and decreased in stator flux in reverse direction at time applied reverse voltage vector$(V_{s,k-1} and\ V_{s,k-2})$. Due to large time constant T_r the rotor flux always lag the stator flux, because due to voltage vector the fastly change in stator flux hence rotor flux is sluggish but in actually the stator flux and rotor flux speed is same [1].

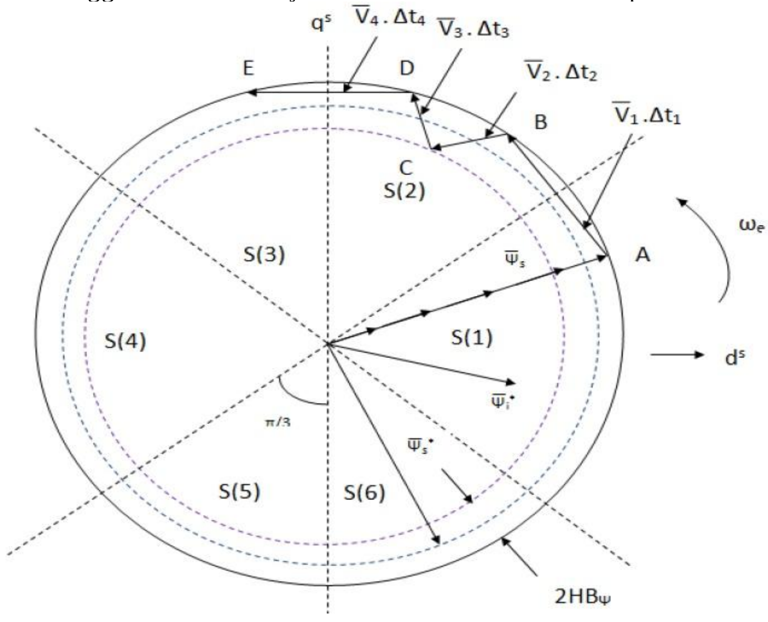

Fig.2 Circular trajectory of stator flux

B. Direct Torque Control: Due to stator and rotor flux interaction the torque is produced. The equation of torque is shown below:

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\frac{L_m}{L_s' L_r}\bar{\varphi}_s \cdot \bar{\varphi}_r = \frac{3}{2}\left(\frac{P}{2}\right)\frac{L_M}{L_s' L_r}\varphi_s\varphi_r \sin\gamma \qquad \text{.................. 2.2}$$

From above equation we have shown that torque proportional to the angle between stator flux and rotor flux i.e γ. we have change in γ fastly so dynamic performance is better. Let us rotor is rotate in anticlockwise and stator flux in K^{th} sector now provide voltage vector $(V_{s,k+1} and\ V_{s,k+2})$ increase γ , due to this torque is increased [1][8].

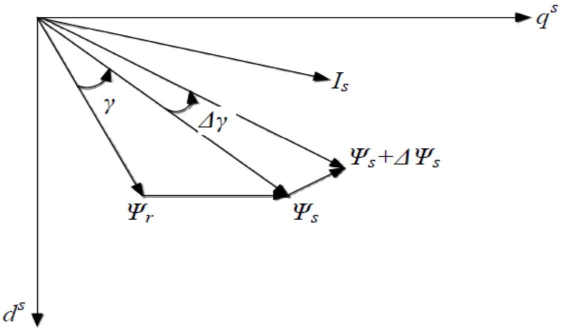

Fig 3 Stator flux, rotor flux and stator current vectors in $d_s - q_s$reference plane

When decreased in γ and T_e then voltage vectors $(V_{s,k}$ and $V_{s,k+3})$ is applied. Torque is decreased while used the reverse voltage vectors $(V_{s,k-1}$ and $V_{s,k-2})$ and when used the zero voltage vector $(V_{s0}$ and $V_{s7})$ the flux is constant and torque is decreased slightly.

C. Switching selection: The control of stator flux and torque in DTC the performance of torque controlled increased, and hence direct torque control known as decoupled controlled. In Figure 3.5 shows the stator flux in sector-1$(S(1))$, and provide appropriate switching voltage vector increased and decreased in torque and flux.

In the switching table or lookup table for selection of appropriate voltage vector in different sector. The error of stator flux, torque is fed to hysteresis band controller and hysteresis band output through generate voltage vector.

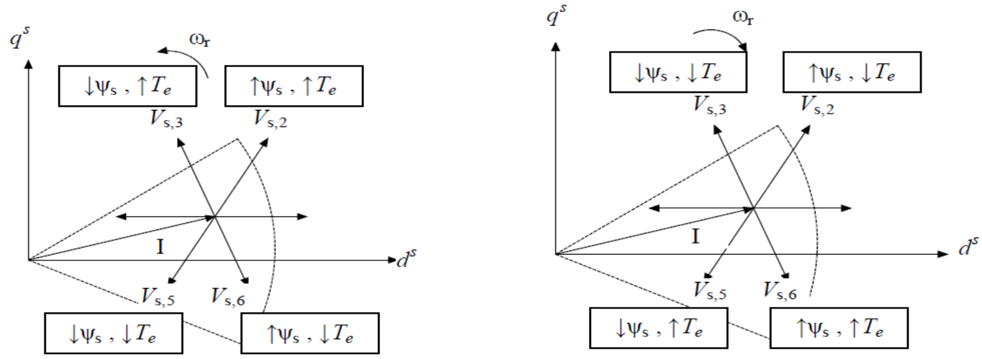

Fig 4 forward active voltage vector for sector 1 (a) Anti-clockwise (b) Clockwise direction

Table 1 : lookup or switching table

$d\varphi$	dTe	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_7	V_0	V_7	V_0	V_7	V_0
	-1	V_6	V_1	V_2	V_3	V_4	V_5
0	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
	-1	V_5	V_1	V_2	V_3	V_4	V_5

D. Hysteresis Controller: In DTC method mainly two hysteresis band controllers is required:

1) Torque hysteresis controller
2) Flux hysteresis controller

The width of hysteresis bands is relate with flux and torque ripples, harmonics in current and switching frequency of electronic device is affected the performance of induction motor drive. Due to small flux hysteresis band the current distortion is reduced and reduced the torque ripple through the small torque hysteresis band, but also switching frequency is increased. Hysteresis controller output change within the sampling interval at that time inverter state remains constant. When hysteresis band is fixed hence switching frequency totally depends on the rate of change of flux and torque.

1. Torque Hysteresis Controller: In torque hysteresis controller consists of 3 level controllers and generate 3 level digital outputs. The value of digital output is $-1,0,1$.when compare the actual torque and reference torque then give the torque errorΔT_e. This torque error fed to hysteresis band, so give the output in term of torque error status ΔT_e. The hysteresis band width is $2\Delta T_e$. This torque error status is given to lookup table for selected appropriate active voltage vector for inverter operation [1] [8].

2. Flux Hysteresis Controller: In flux hysteresis controller consists of 2 level controllers and generate 2 level digital outputs. The value of digital output is 0 *and* 1. When the compare actual flux and reference flux then generate the flux error$\Delta\Psi_s$. This error is fed to flux hysteresis band and give the output in terms of flux error status $d\Psi_s$. This flux error status is given to the lookup table for selected voltage vector for inverter operation.

III. 12 SECTOR METHODOLOGY

Table 6.2 12 Sector Methodogy

Sector No.	Degree
Sector 1	$0° \ to \ 30°$
Sector 2	$30° \ to \ 60°$
Sector 3	$60° \ to \ 90°$
Sector 4	$90° \ to \ 120°$
Sector 5	$120° \ to \ 150°$
Sector 6	$150° \ to \ 180°$
Sector 7	$180° \ to \ 210°$
Sector 8	$210° \ to \ 240°$
Sector 9	$240° \ to \ 270°$
Sector 10	$270° \ to \ 300°$
Sector 11	$300° \ to \ 330°$
Sector 12	$330° \ to \ 360°$

The 12 sector methods is same as work as conventional DTC work but in conventional DTC 6 sector and in modified DTC 12 sector uses plus 5 level torque hysteresis band controller is used it gives digital output like 2,1,0,-1,-2.

In table 2 shows that 12 sector method is implemented in modified DTC scheme, in conventional DTC scheme 1st sector will be start from $-30° \ to \ 30°$ but in 12 sector method the 1st sector start from$0° \ to \ 30°$.

In modified DTC scheme used new switching table with help of 5 level torque hysteresis band controllers, 2 level flux hysteresis band controllers and switching sector. Due to use the modified look up table we can change in small amount of torque and flux, also reduced in torque ripple and improves in drive performance in low speed range operation.

A. 12 sector lookup table for modified DTC scheme:

Table 3 Modified Lookup Table

$d\varphi$	dTe	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)	S(7)	S(8)	S(9)	S(10)	S(11)	S(12)
1	2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2
1	1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1

1	0	V_0	V_7	V_0	V_7	V_0	V_7	V_0	V_7	V_0	V_7	V_0	V_7
1	-1	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6
1	-2	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6
-1	2	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3
-1	1	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4
-1	0	V_7	V_0	V_7	V_0	V_7	V_0	V_7	V_0	V_7	V_0	V_7	V_0
-1	-1	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4
-1	-2	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5

B. Trajectory of Stator Flux Vector:

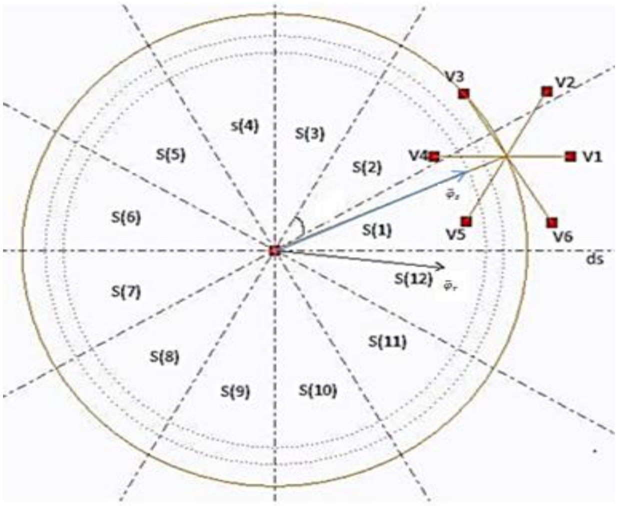

Fig 5 Trajectory of stator flux vector for 12 sector

in table 3 shows that the modified lookup table. In fig. 5 shown the trajectory of flux this flux is in sector 1 now when increased and decreased in torque and flux than used total 8 voltage vectors. Suppose $dT_e = 2$ and $d\varphi = 1$ then apply V_2 hence increase the angle in anticlockwise so torque increase also flux increase hence maintain the speed of motor.

IIII. SIMULATION RESULTS

The basic DTC and the new 12 sector method of DTC are simulated and the results obtained are compared for their Performance in Fig, for steady state.

Figure 6 shows the electromagnetic torque, rotor speed, stator flux and stator current of the machine for 100% rotor speed, However, there is some performance degradation with torque overshoot in the torque transient and torque ripple is generated owing to the hysteresis controllers used.

In fig 6 shows that at higher speed (150rad/sec) voltage model estimate accurate stator flux or we can say low distortion in estimated flux so low torque ripple in higher speed but when low speed range operation performed (Ex.15rad/sec) then voltage model estimate inaccurate flux measurement so produce large torque ripple also more distortion in stator current. Mainly due to hysteresis band controller produced large torque ripple, so below section shown 12 sector methodologies for reduce large torque ripple and total harmonic distortion.

The torque is increased at starting time due to increase load torque this point is accelerating zone and after decreased and after all remain constant also shows that the flux increases in starting point and after remain constant to control the torque.

In fig 7 shows that when motor perform low speed operation at time torque is overshoot in the torque transient owing to the hysteresis controllers used and also some performance degradation in stator currents.

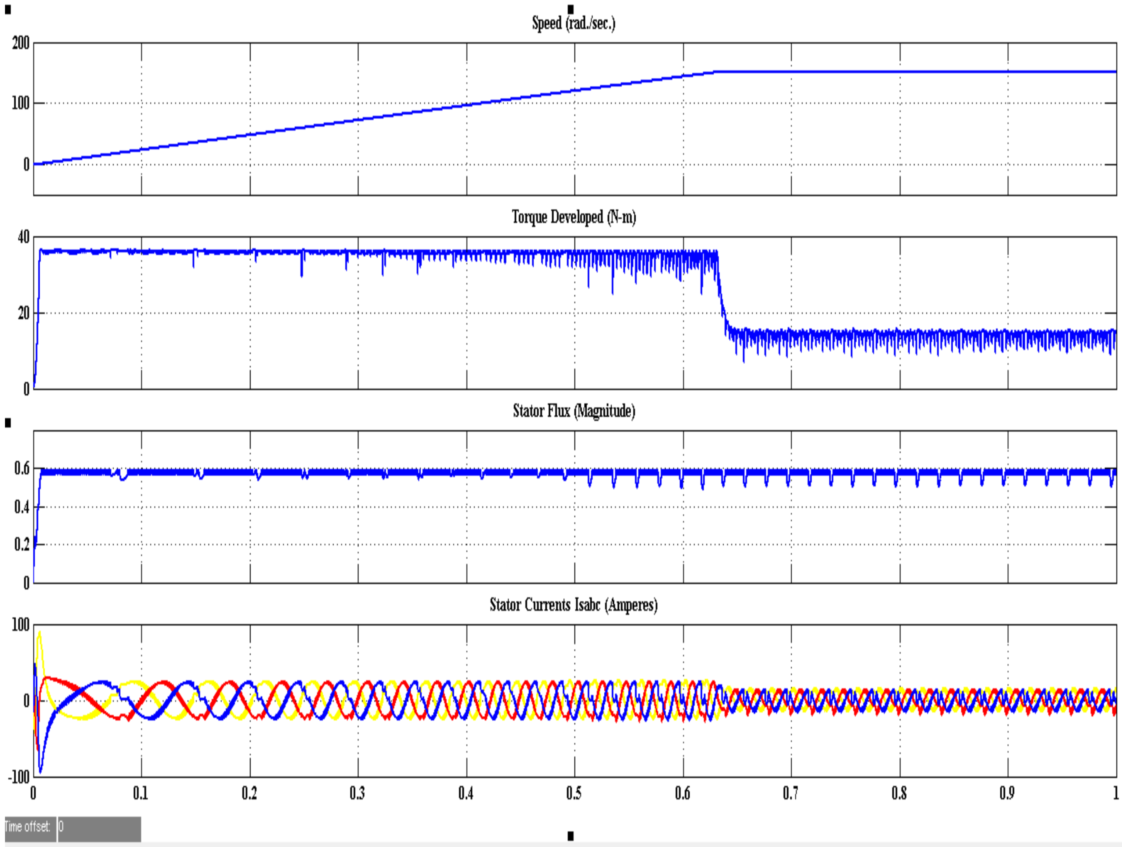

Fig: 6 Simulation result for conventional DTC scheme ω=150 rad/sec, torque= 14.25 N.m, stator flux= 0.58 wb

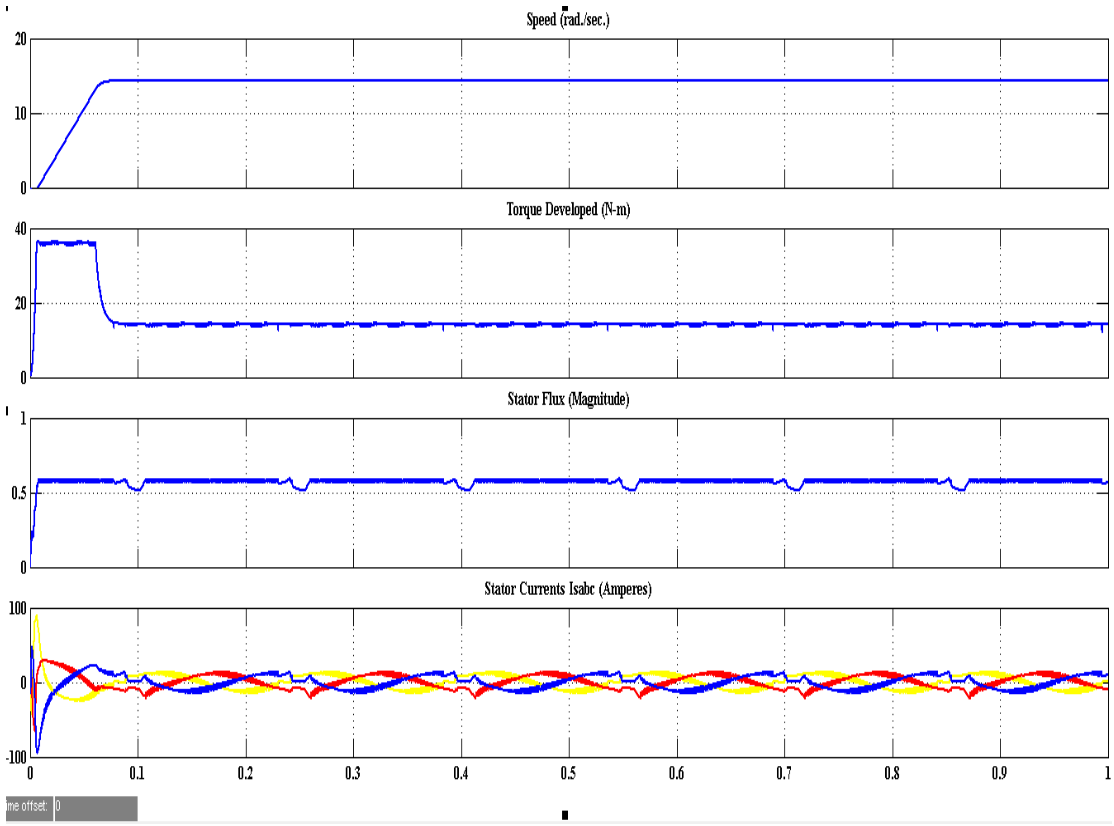

Fig 7 Simulation result for conventional DTC scheme ω=15 rad/sec, torque=14.25 N.m, stator flux=0.58 wb

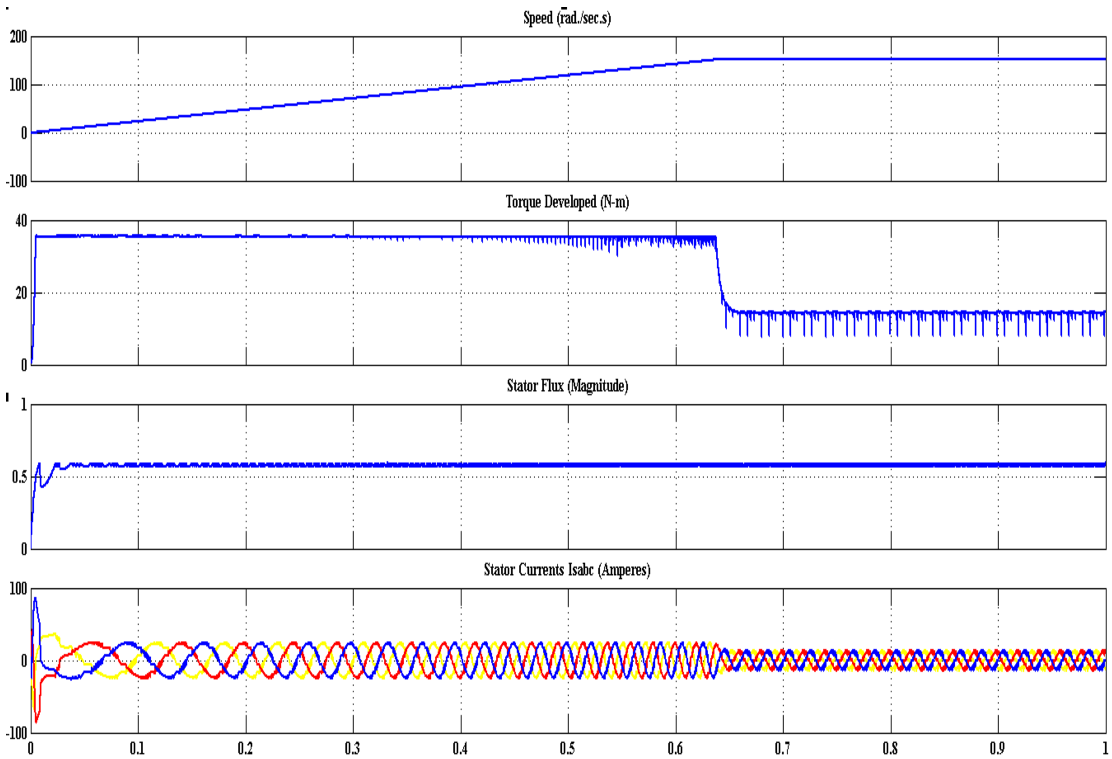

Fig 8 Simulation result of modified DTC scheme for ω=150 rad/sec, torque=14.25 N.m, stator flux=0.58 wb

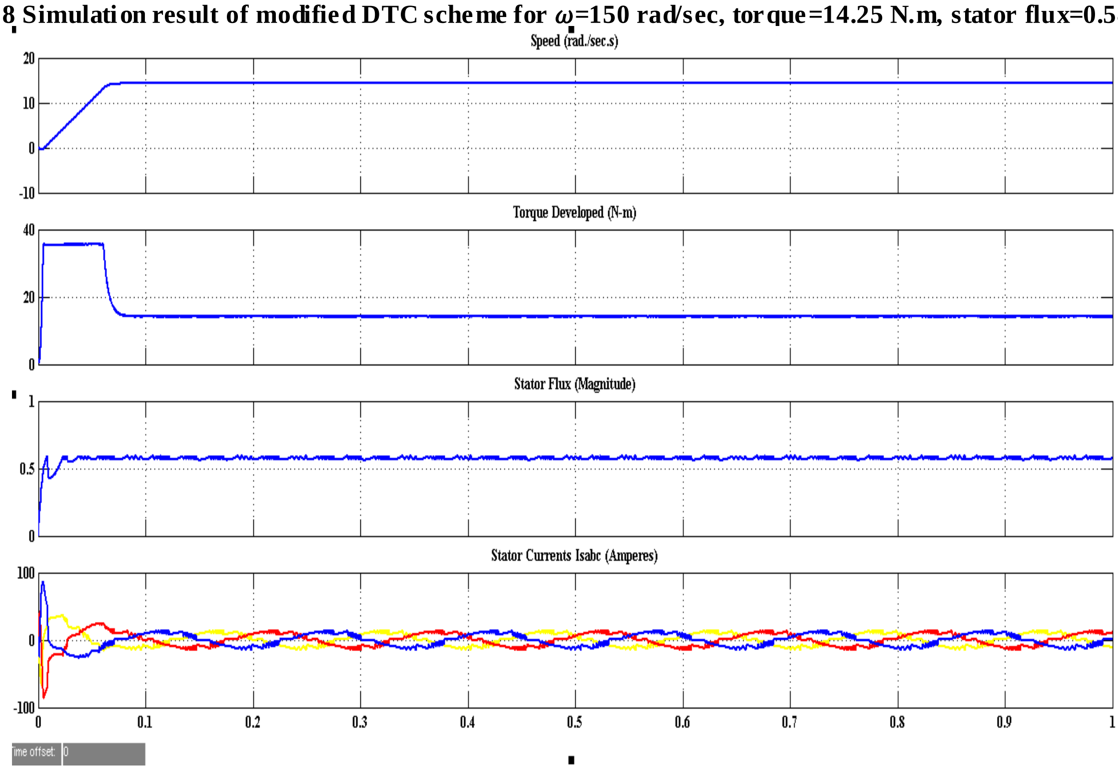

Fig 9 Simulation result of modified DTC scheme for ω=15 rad/sec, torque=14.25 N.m, stator flux=0.58 wb

From above modified DTC simulation (12 sector) we can see that at lower speed (15rad/sec) give accurate flux estimation.so DTC drive produce low torque ripple and also less distortion in stator current.

In this result we can say that torque ripple and current distortion is reduce compare to conventional DTC scheme. hence we can say that the 12 sector modified DTC scheme is used for when low speed range operation is performed, so in conventional DTC scheme the large torque ripple in low speed and also medium speed hence used the modified DTC scheme this problem is overcome.

IV. CONCLUSION

In Recent year the induction motor drives direct torque control strategies is best controller. It is decoupled control because speed control from change in flux and torque. Direct torque control strategies of induction motor control is simpler because it easy to implement than vector control strategies and also DTC has no required any co-ordinates transformation and pulse width modulation technique, but in low speed range operation the undesirable torque ripple and stator current distortion produced, reduced the torque ripple by improved in lookup table hence improve the direct torque strategies for of induction motor in low speed range operation. I carried out MATLAB SIMULATION of Conventional DTC scheme and Modified DTC scheme. In modified DTC scheme included 12 sector methodology, 5 level torque hysteresis band controllers.

IV. APPENDIX

The parameter of 3 phase induction motor employed for simulation purpose is given below:

Motor Parameter

output Power:	**3 hp**
Voltage(Line to Line):	**220 V**
Frequency:	**50 Hz**
Stator resistance:	**0.435Ω**
Stator Inductance:	**0.002H**
Rotor Resistance:	**0.816Ω**
Rotor Inductance:	**0.002H**
Mutual Inductance	**.06931H**
Inertia:	**0.089(kg.m^2)**
Friction Factor:	**0 (N.m.s)**
Pole Pairs:	**2**

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