Improved Direct Torque Control strategy for Wide Range Speed Control of Induction Motor Drives

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Abstract: Abstract—Induction Motor is popular option for most of the drives applications. It has simple construction but complex control. DC motor like decoupled control of induction motor drives similar to Field Oriented control is possible using Direct Torque Control (DTC) method which is very simple control strategy compared to vector control. The DTC strategy is very useful for automobile and traction applications using IM but due to use of hysteresis band controllers, DTC has problems of torque ripples, variable switching frequency and poor low speed performance. Because of these reasons, DTC is used in such applications for high speed range and not for the whole speed range. An improved DTC strategy suitable for wide range speed control is suggested in this paper which is based on a performance index calculated on the basis of what is the value of THD of stator current, value of operating speed and switching frequency. It uses new five level variable width torque hysteresis band controller and two level variable width hysteresis band flux controller along with new hybrid model for stator flux estimation. This improved strategy is designed to maintain simplicity of conventional DTC and give better performance than it. This new strategy is simulated using Matlab/Simulink

Keywords: DTC, Electric Vehicles, Traction drives, Induction motor drives.

I. INTRODUCTION

Induction Motors enjoy lions share in industrial applications, locomotives and domestic applications. Their limitation of difficulty in speed control is also eliminated with the advent of power electronics, advanced controllers and control algorithms like scalar control, field oriented control and Direct Torque Control [1][2]. High dynamic performance of IM comparable to Vector controlled drives can be achieved using DTC [3][4] without complex co-ordinate transforms and PWM algorithms. Also DTC algorithm is simple, robust and inherently speeds sensor-less. The features of direct torque control are specifically more suitable to Electric Vehicles (EV) and traction applications where induction motors are making their mark[5][6].The problems encountered in conventional DTC are torque ripples, poor low speed region working and variable switching frequency. These problems are more serious at low speed with heavy loads[7].

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Many methods have been suggested in research literature to address these problems[8][9][10][11]. Methods for performance improvement of classical DTC can be classified in four categories as: (1) DTC with modified lookup table methods (2) DTC with constant switching frequency using SVPWM (3) DTC with predictive control (4) DTC with neuro-fuzzy controller [8-11]. None of the methods mentioned above are suitable for wide range speed applications. Also, conventional DTC scheme is popular for its robustness and simplicity while these modified DTC strategies are complex and parameter dependent.

Here a modified DTC controller is presented which implements a variable width five level hysteresis band torque controller and two level variable width hysteresis band flux controller whose width is varied as per a performance index calculated based on value of operating speed, switching frequency and THD of stator current. Separate new lookup tables are implemented for low speed and high speed ranges. Also, a hybrid flux estimator is used which uses two different flux estimation modes for low speeds and high speeds. To test the performance, a simulation model is prepared for proposed strategy using Matlab/Simulink.

II. CLASSICAL DTC

In classical DTC scheme one voltage vectors selected out of six active voltage vectors and two zero voltage vectors generated by the voltage source inverter. The selection is done in such a way that torque and stator flux remains within bands of two hysteresis bands. Systematic use of this strategy results into decoupled control of IM without complex co-ordinate transformations, current regulators or PWM pulses.

The torque developed by induction motor is directly proportional to angle between rotor flux vector and stator flux vector as shown in following equation.

$$T_e = \frac{L_m}{\sigma L_s L_r} \psi_s \psi_r \sin\gamma_{sr} \qquad (1)$$

The vector of rotor flux always follows that of the stator flux. By advancing the stator flux vector in phase, angle γ_{sr} can be increased and so the torque developed increases. Similarly by reducing angle γ_{sr}, torque can be reduced. In short direct torque control is possible just by changing position of stator flux vector with reference to rotor flux vector. In classical DTC this movement of stator flux is achieved by selection appropriate switching voltage vector of VSI.

Appropriate inverter voltage space vector is selected based on stator flux error and torque error such that stator flux and torque remain within a hysteresis band. Fig.1 shows six active and two non-zero voltage space vectors which are possible for two level VSI.

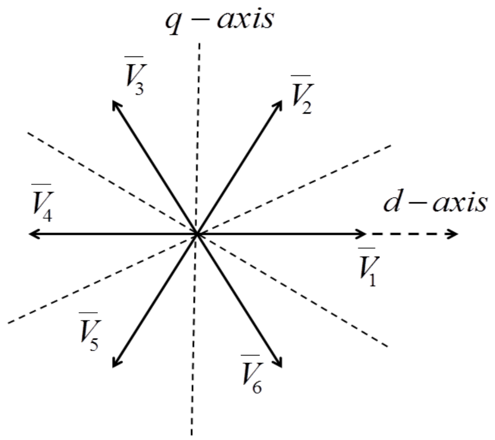

Fig. 1 Voltage space vectors

Complete block diagram of classical DTC scheme is shown in Fig. 2, where T_e^* and ψ_s^* are reference torque and reference stator flux respectively. Torque error and stator flux errors are processed by three level and two level hysteresis band controllers to generate status signals dT_e and $d\psi_s$ respectively. Based on status of dT_e, $d\psi_s$ and sector $\theta(i)$, suitable voltage switching space vector is selected form lookup table to give fast dynamic response and to maintain torque error and stator flux error within hysteresis band. Table-I shows the lookup table used to generate switching voltage vector of VSI.

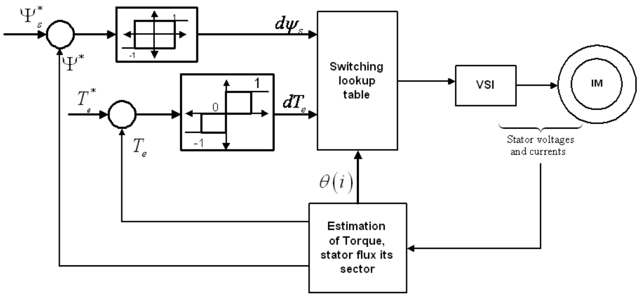

Fig. 2 Block diagram of conventional DTC scheme

Torque, stator flux magnitude and the sector in which stator flux vector is placed at any instant can be estimated from stator voltages and stator currents. Following equations are used to estimate torque, stator flux and sector information

Table 1 Lookup table for switching voltage vectors

$d\psi_s$	dT_e	$\theta(1)$	$\theta(2)$	$\theta(3)$	$\theta(4)$	$\theta(5)$	$\theta(6)$
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
-1	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_6	V_1	V_2	V_3	V_4

$$\psi_{ds} = \int (V_{ds} - R_s i_{ds})dt \qquad (2)$$

$$\psi_{qs} = \int (V_{qs} - R_s i_{qs})dt \qquad (3)$$

$$\psi_s = \sqrt{\psi_{ds}^2 + \psi_{qs}^2} \qquad (4)$$

$$\theta = \tan^{-1}\left(\psi_{qs} / \psi_{ds} \right) \qquad (5)$$

$$T_e = \frac{3}{2}\frac{P}{2}(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \qquad (6)$$

Striking advantages of this method is that it achieves decoupled control of torque and flux without complex co-ordinate transformations or PWM signal generation. It only depends on stator resistance hence it is a robust control method. It gives dynamic response quite comparable to vector control but it has some of the drawbacks which are discussed in the following section.

III. PROBLEMS IN CLASSICAL DTC

Following are the problems of conventional DTC in case of wide range speed control applications.

1) THD in the stator current is more.
2) By increasing width of hysteresis band torque controller, torque ripple increases and decreasing width results into increased switching frequency.
3) Increasing sampling time deteriorates the performance of the drive.
4) At low speed the drive performance is poor.
5) At low speeds, error in estimated stator flux is more due to stator resistance voltage drop, an improved stator flux estimation in low speed range will improve the performance.
6) Switching frequency is variable

Following deductions can be made from the study of conventional DTC: (1) width of hysteresis band torque and flux controller is affecting torque ripple, dynamic response of the drive, switching frequency and THD of stator current. (2) At different operating speeds the required width of H.B. controller for satisfactory performance is different. (3) Proper adjustment of width of H.B. controller with operating speed will give improved performance. (4)New algorithm should be simple, requiring less computations time so that fast sampling can be done which reduces the torque error.(5) At low speeds the locus of stator flux is not circular but more like a hexagon. This results into non sinusoidal waveform of stator flux giving rise to harmonics in stator currents. Also, the switching at sector transition is very low which give rise to variable switching frequency. Thus operation of DTC induction motor drive at low speed is a challenge.

IV. NEW CONTROL STRATEGY FOR DTC

Fig.3 shows block diagram of modified direct torque controlled induction motor drive in which DTC controller is modified to get improved performance suitable for wide range speed control as shown in deductions after analysis. Various blocks of modified DTC controller are shown in Fig. 4 where in hysteresis band torque and flux controller are modified to have adjustable width of hysteresis band as per value of performance index K. Torque hysteresis band is changed from

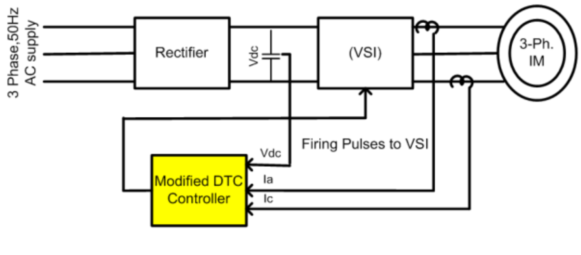

Fig. 3 Block diagram of modified DTC

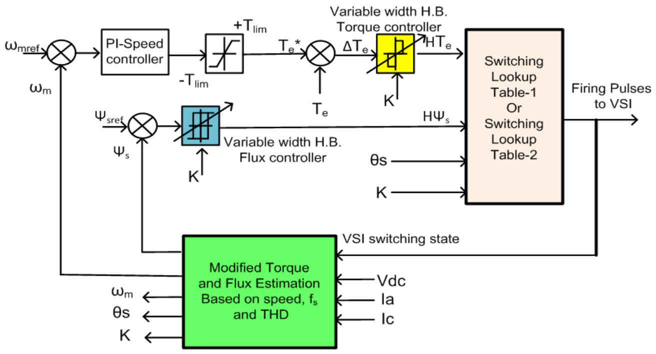

Fig. 4 Improved DTCcontroller for wide range speed control

three level to five level as new switching table is suggested for low speed operations. Flux estimator is also changed in modified DTC scheme. Flux estimation method is selected based on performance index K. Highlights of New algorithm are:

· Performance index-K is calculated which is function of operating speed in steady state, switching frequency in steady state and total harmonic distortion of stator current in steady state.

· $$K = a*\omega_r + b*f_s - c*THD \qquad (7)$$

Its value is designed to be in the range of 0-100.

· If K < boundary Value, operation is changed to the one suitable for low speed operation, i.e Reduced width of H.B. Torque and Flux controller, Flux estimation method is changed and sector division is changed from 6 to 12,Improved switching lookup table suitable for low speed operation is selected.

If K > boundary Value, operation is changed to the one suitable for high speed operation, i.e. increased width of H.B. Torque and Flux controller, conventional flux estimation method and sector division is changed from 12 to 6 and conventional switching lookup for high speed operation is selected

· During low speed operation, switching frequency is less and THD in stator current is more. So, if speed is low, switching frequency is low and THD of stator current is high, K < boundary value.

· New 12-sector division of stator flux locus is shown in Fig.5. The stator flux locus has six sectors of sixty degrees each in conventional DTC. In this method one voltage vector is applied for the whole sampling period irrespective of the instantaneous requirements. Also all the voltage states are not used in case of six sectors. In case of conventional DTC if V_1 and V_4 if used for stator flux vector in first sector, they can improve the torque and stator flux, but they are not used. This is possible if the position of stator flux vector is known to be in first thirty degrees of sector one or not. To take advantage of it the stator flux locus is divided into twelve sectors instead of just six in modified DTC strategy.

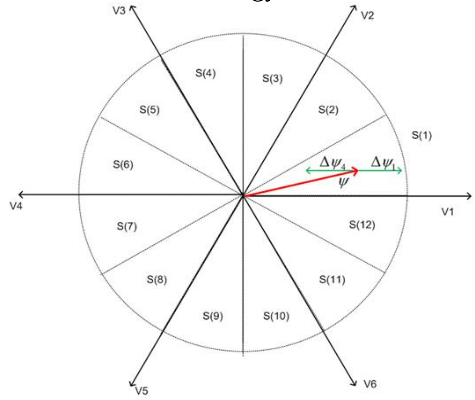

Fig. 5 New 12-sector division for new switching voltage vector selection

Table- II shows division of 12 sectors using which new lookup table is designed which is suitable for low speed operation. It is indicated by K<50 here. In low speed region, it is more accurate if we estimate stator flux using speed and current signals. Fig. Fig.6 shows rotor flux estimation using current model in stationary reference frame.

Table 2 New lookup table for switching voltage vector selection

$d\psi_s$	dT_e	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}
	+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	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	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6
	−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
	+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	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	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4
	−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

A hybrid flux estimation technique is proposed which uses current model estimation for K < 50 and conventional voltage model flux estimation technique for K > 50.

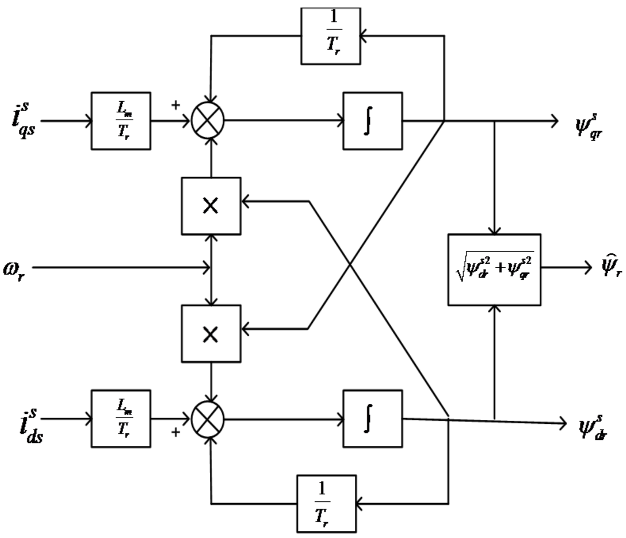

Fig. 6 Modified flux estimation block

Following equations show method of estimating stator flux and its position using this information.

$$\psi_{dm}^{s} = \left(\frac{L_m}{L_r}\right)(\psi_{dr}^{s} + i_{ds}^{s} L_{lr}) \qquad (8)$$

$$\psi_{qm}^{s} = \left(\frac{L_m}{L_r}\right)(\psi_{qr}^{s} + i_{qs}^{s} L_{lr}) \qquad (9)$$

$$\psi_{qs}^{s} = \psi_{dm}^{s} + i_{ds}^{s} L_{ls} \qquad (10)$$

$$\psi_{qs}^{s} = \psi_{qm}^{s} + i_{qs}^{s} L_{ls} \qquad (11)$$

$$\psi_{s}^{s} = \sqrt{\psi_{ds}^{s2} + \psi_{qs}^{s2}} \qquad (12)$$

$$\theta = \tan^{-1}\left(\psi_{qs}^{s} / \psi_{ds}^{s}\right) \qquad (13)$$

V. SIMULATION RESULTS

Simulation was carried out with conventional and improved DTC strategy for 100%, 80%, 60%, 40%, 20% and 10% of rated speed. Fig.7 to Fig. 12 show simulation results of conventional DTC and modified DTC induction motor drive, side by side. A 200 h.p., 460 V, 1433 rpm, 50 Hz , three phase, 4-pole , star connected, squirrel cage induction motor with parameters: R_s= 0.01818 , R_r=0.009956 , L_{ls}= L_{lr}= 0.00019 H, L_m=0.009415H, J= 2.6 Kg-m^2 is selected for simulation. For which Rated speed ω_m = 150 rad./sec., full load torque Te= 800 N-m and full load current= 220 A.

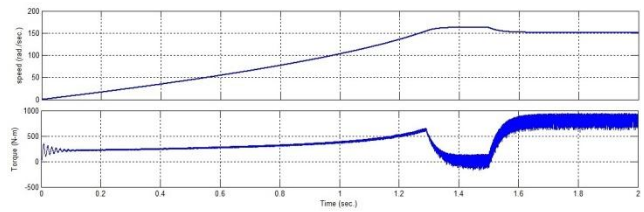

Fig. 7 Speed and torque variations with conventional DTC

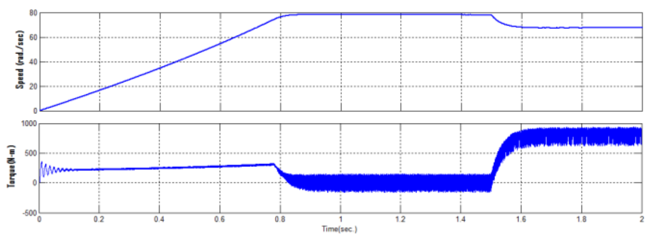

Fig. 8 Speed and torque variations with modified DTC

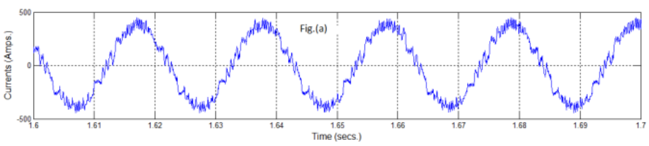

Fig. 9 Stator currents with conventional DTC

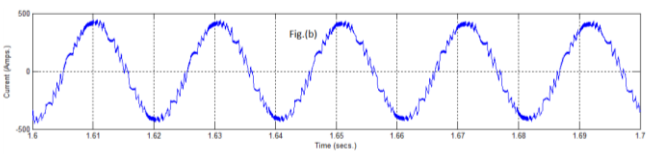

Fig. 10 Stator current waveform with modified DTC

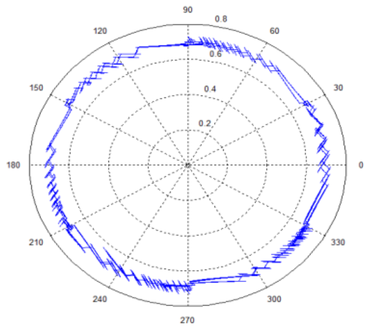

Fig. 11 Polar plot of stator flux variation with conventional DTC

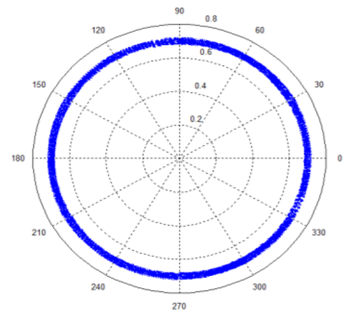

Fig. 12 Polar plot of stator flux variation with modified DTC

Table 3 Comparison of THD for conventional and modified DTC

Sr.No.	Speed (rad./sec)	Max. Switching frequency fs(KHz)	Performance index K	%THD with conventional DTC	%THD with Modified DTC	New Max. switching frequency fs(KHz)
1	150 (100%)	2.97	69	12	12	2.97
2	120 (80%)	2.85	58	13.2	13.2	2.85
3	90 (60%)	2.67	54	13.8	13.8	2.67
4	60 (40%)	2.49	47	14.6	12.3	2.8
5	30 (20%)	1.64	37	17	8.3	2.83
6	15 (10%)	1.53	29	18.7	9.7	2.95

Table 4 Comparison of torque ripples for conventional DTC and modified DTC

Sr.No.	Speed (rad./sec)	Performance index K	Torque ripple with conventional DTC		Torque ripple with Modified/Improved DTC	
			N-m	%	N-m	%
1	150 (100%)	69	110	13.75	110	13.75
2	120 (80%)	58	110	13.75	110	13.75
3	90 (60%)	54	110	13.75	110	13.75
4	60 (40%)	47	115	14.37	60	7.5
5	30 (20%)	37	120	15.00	40	5.0
6	15 (10%)	29	100	12.5	30	3.75

It can be seen that THD in stator current is much less with modified DTC compared to conventional DTC. Stator flux estimation is also improved with modified DTC strategy. Table-01 shows that switching frequency is different at different operating speeds for conventional DTC strategy while it is almost constant with modified DTC strategy.

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VI. CONCLUSION

Classical DTC method is having many advantages like inherent speed sensor less control, dependence on stator resistance only, no need for current controllers and simplicity with high performance. The problems associated with classical DTC are torque ripples, variable switching frequency and inferior performance at low speed operation with heavy load. For wide range speed control applications these problems become pronounced. Many methods are reported to improve performance of classical DTC strategy, but no single method is suitable for wide range speed control application like Electric vehicles or traction. The modified DTC method proposed here maintains the simplicity of the technique and makes it suitable for wide range speed control applications like Electric Vehicles or traction. It also gives almost constant switching frequency.

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