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Direct Torque Control Algorithm for Induction Motor Using Hybrid Fuzzy-PI and Anti-Windup PI Controller with DC Current Sensors

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Abstract
In this paper, torque ripple minimization in direct torque control (DTC) of three phase Induction Motor (IM) using PI, hybrid fuzzy PI and anti-windup PI controller were compared. Speed performance is also improved when the controllers were changed. Reconstruction of phase current method is used in the conventional method, by using this method cost of the sensors is reduced and also basic DTC performance is maintained. The reference speed is used for generating the reference torque with the help of PI controller. The drawback is torque ripple in induction motor by using the existing DTC. In proposed system, controller of hybrid fuzzy-PI and anti-windup PI were implemented for generating the reference torque. The speed performance is improved by hybrid Fuzzy-PI controller and the torque ripples will be minimized by using the anti-windup PI controller. The proposed method is implemented using MATLAB/SIMULINK.
Keywords*:* Induction motor, direct torque control, Hybrid Fuzzy-PI controller, Anti-windup PI controller.

I.INTRODUCTION

The basic concepts of DTC induction motor drives are used for controlling the stator flux and also electromagnetic torque. The DTC is derived on the basis of the error between the reference and estimated valves of torque and flux. In general, galvanically isolated current sensors such as Hall-effect sensors and current transducers are widely used in many applications. Recently, single current sensor operation has been proposed to reconstruct phase currents from the dc-link current sensor. The DTC scheme is applied for the estimation of speed and a torque control.

DTC is characterized by directly controlling the flux and torque and indirectly controlling the voltage and stator current. It is also said to be as vector control. The greatest view in DTC has some of the advantages ,

- The control is associated without using current loops.
- The use of pulse-width modulation (PWM) is not necessary.
- The drive does not need of any coordinate transformation.

There are few disadvantages also present

- At low speed it is difficult to control flux and torque
- During the sector change having current and torque distortion
- To implement the hysteresis controllers need of high sampling frequency
- Presence of high torque ripple.

In (1986) proposed an algorithm which is a new technique of induction motor which response is quick and also - efficiency is high, and it is different from the field-oriented control. The principle of it is based on limit cycle control, and it makes possible both quick torque response and high-efficiency operation at the same time. In (2012) proposed a technique to implement a torque control scheme, based on a direct torque control (DTC) algorithm using for a variable speed control 12-sided polygonal voltage space Vector is used for an induction motor drive which is in the form of open-end.

In (2011) proposed a optimization technique on the duty ratio of active vector to decrement the torque and flux ripple. Three methods of determining the duty ratio are explained and efficient method is suggested. In (2006) proposed a technique of direct torque control (DTC) based induction motor (IM), here single current sensor is used in the dc link of the inverter.

The oscillation of electromagnetic torque is due to the stator flux vector movement during the sectors changes. Another important issue is the achievement of hysteresis controllers which involves greater sampling frequency. The digital signal processor is implemented for operating the hysteresis controller is quite different to the analogue operation. Speed performance is improved when hybrid fuzzy-

PI controller is implemented. To reduce the torque ripples in induction motor anti-windup PI controller is also implemented.

II.INDUCTION MOTOR MODELING

Equivalent circuit of induction motor is shown in the Figure 1 & 2.

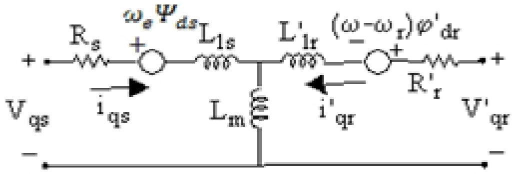

Figure 1 q- axis

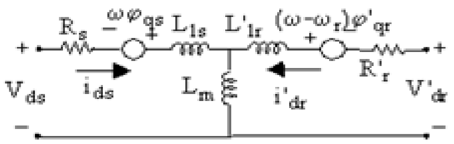

Figure 2 d- axis

Stator voltage equations can be referred in d^e-q^e axis as

$$\begin{cases} v_{qs} = R_s i_{qs} + \frac{d}{dt}\psi_{qs} + \omega_e \psi_{ds} \\ v_{ds} = R_s i_{ds} + \frac{d}{dt}\psi_{ds} - \omega_e \psi_{qs} \end{cases} \tag{1}$$

Rotor voltage equations can be referred in d^e-q^e axis as,

$$\begin{cases} V_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + (\omega_e - \omega_r)\psi_{dr} \\ V_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} + (\omega_e - \omega_r)\psi_{qr} \end{cases} \tag{2}$$

Equation for flux linkage is expressed as,

$$\begin{cases} \psi_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) \\ \psi_{qr} = L_{lr} i_{qr} + L_m (i_{qs} + i_{qr}) \\ \psi_{qm} = L_m (i_{qs} + i_{qr}) \\ \psi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) \\ \psi_{ds} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) \\ \psi_{dm} = L_m (i_{ds} + i_{dr}) \end{cases} \tag{3}$$

Substituting the equation (3) in voltage equation (1) & (2) torque equation is obtained as,

$$T_e = \frac{3}{2}(\frac{P}{2})(\psi_{dm} i_{qr} - \psi_{qm} i_{dr}) \tag{4}$$

III.DTC SCHEME

The implementation of the DTC scheme requires flux linkages and torque computations and lacking of inner loop of current, the switching states is generated with the help of feedback torque and flux. The flux and torque is analyzed for applying the control loop, which is approximated by the voltages and currents of the stator. To achieve the need torque output the switching table is used to establish the suitable inverter state. By means of current and voltage extent, it is feasible to compute approximately the instantaneous stator flux and output motor torque. The control algorithm based on flux and torque hysteresis controllers determines the voltage required to drive the flux and torque to the desired values within a fixed time period. The DTC method is characterized in the form of basic functional block.

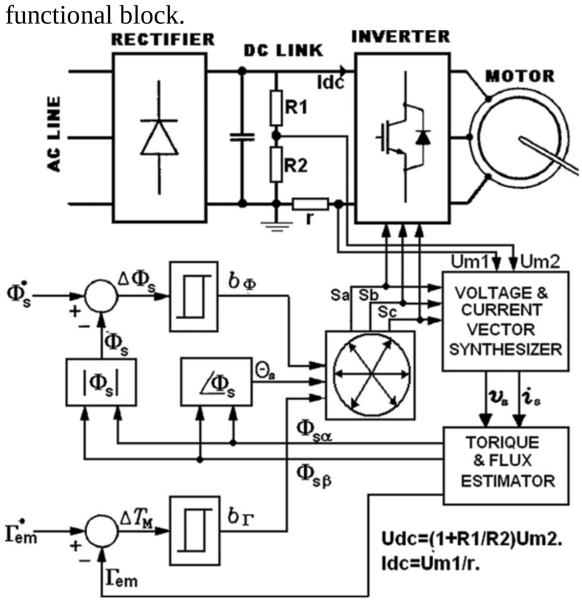

Figure 3 Conventional DTC

The stator flux vector $\vec{\phi_s}$ and the torque is generated in the motor, τ_{em}, and approximated by the voltage vector V_s, which is related to the preceding knowledge and calculated current, resistance in stator, number of poles in motor p. The approximation of torque and magnitude of stator flux, a hysteresis control is completed and then vectors of voltage is to be approximated which are achieved in the switching Table [1]. The reference frame which is perpendicular to the voltage in the stator components is resulted from exact voltage in dc-link U_{dc} and the logical states of switching controls S_a , S_b, and S_c is given by,

$$\begin{cases} V_{s\alpha} = \sqrt{\frac{2}{3}} U_{dc} \left(S_a - \frac{1}{2(S_b - S_c} \right) \\ V_{S\beta} = \frac{1}{\sqrt{2}} U_{dc} \left(S_b - S_c \right) \end{cases} \tag{5}$$

And stator current components (I_α, I_β)

$$\begin{cases} I_{S\alpha} = \sqrt{3/2} I_a \\ I_{S\beta} = 1/2 \sqrt{(I_b - I_c)} \end{cases} \tag{6}$$

The stator resistance can be assumed constant. During a switching period, the voltage vector applied to the motor is constant [1]. By integrating the back electromotive force (EMF), the stator flux can be estimated using,

$$\begin{cases} \phi_{s\alpha} = \int (V_{s\alpha} - R_s I_{s\alpha}) dt \\ \phi_{s\beta} = \int (V_{s\beta} - R_s I_{s\beta}) dt \end{cases} \tag{7}$$

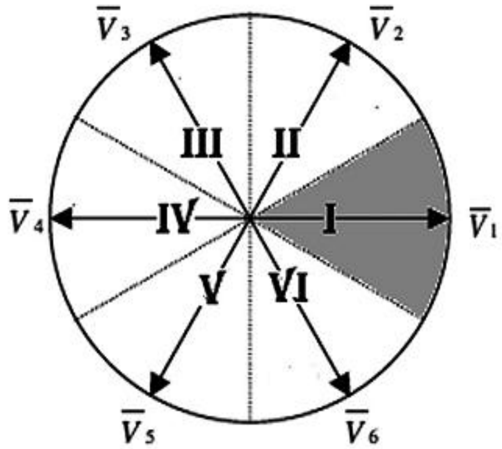

Figure 4 DTC sectors and inverter voltage vectors

During the switching period, each voltage vector is constant and equation can be rewritten as,

$$\begin{cases} \phi_{s\alpha} = \phi_{s\alpha} + (V_{s\alpha} - R_s I_{s\alpha}) T_s \\ \phi_{s\beta} = \phi_{s\beta} + (V_{s\beta} - R_s I_{s\beta}) T_s \end{cases} \tag{8}$$

Table 1 Basic DTC Switching Table

b □	**b □**	**Sector I**	**Sector II**	**Sector III**	**Sector IV**	**Sector V**	**Sector VI**
1	**1**	$\mathbf{V_5}$	$\mathbf{V_6}$	$\mathbf{V_1}$	$\mathbf{V_2}$	$\mathbf{V_3}$	**V4**
	0	$\mathbf{V_3}$	$\mathbf{V_4}$	$\mathbf{V_5}$	$\mathbf{V_6}$	$\mathbf{V_1}$	$\mathbf{V_2}$
0	**1**	$\mathbf{V_6}$	$\mathbf{V_1}$	$\mathbf{V_2}$	$\mathbf{V_3}$	$\mathbf{V_4}$	$\mathbf{V_5}$
	0	$\mathbf{V_2}$	$\mathbf{V_3}$	$\mathbf{V_4}$	$\mathbf{V_5}$	$\mathbf{V_6}$	$\mathbf{V_1}$

The magnitude of the stator flux can be estimated by,

$$\phi_s = \sqrt{(\phi_{s\alpha} + \phi_{s\beta})^2} \tag{9}$$

We can find the flux vector zone using the stator flux components ($\phi_{s\alpha}$, $\phi_{s\beta}$). The electromagnetic torque is estimated by the following parameters i.e., component of flux, current and number of poles in IM.

$$\tau_{em} = 3/2\, p(\phi_{s\alpha} I_{s\beta} - \phi_{s\beta} I_{s\alpha}) \tag{10}$$

For the operation of inverter, the switching combinations of vectors are two zero- voltage and the similar amplitude used for the six identical voltage vector which is explained in the figure 1. In the hysteresis bands the torque and flux is maintained for deciding the voltage vectors.

A.SINGLE CURRENT SENSOR

The basic DTC scheme requires two current sensors at least. The DTC scheme described in this paper uses only one shunt resistor for dc link current measurement

B.DC-LINK CURRENT SAMPLING AND RECONSTRUCTION OF STATOR CURRENT

One of the most significant reasons for reconstruction of three phase using single-shunt is cost minimization. So that the sampling circuit is simplified and it reduces into single shunt resistor. The single-shunt algorithm allows the use of power modules which does not afford for each phase, individual ground connection. An additional advantage of single shunt measurement is that to sense all the three phases same circuit is used.

IV.HYBRID FUZZY-PI CONTROLLER

Mostly in controllers PI Proportional plus integral controller is used. In PI controller gain and time constant is fixed but the performance is affected by variations in parameter, speed and disturbance in load.

The problems with PI controller can be solved with the help of fuzzy logic controller. Mathematical model is not needed for fuzzy logic controller and it is depends on the linguistic rules which is acquired from the knowledge of system operator. Under transient condition only effect of the fuzzy logic controller is better than the PI controller. According to the input error signal the gain of the PI controller is varied. The PI controller suffers due to the problem of exact performance, and the controller limits, gains and the rate of change which should be chosen appropriately. In steady state condition PI controller has better performance than fuzzy controller. The compensation of the controllers of fuzzy and PI is attained with the controller of hybrid fuzzy-PI ,where in the near steady state conditions the active controller is PI and in conditions like transient the active controller is fuzzy.

V.ANTI- WINDUP PI CONTROLLER

The most important purpose of Anti-Windup scheme is to keep the Integrator value within limits. So that the output of integrator will be maintained within a limited range. The saturation of output from controller can be caused due to two reasons i)large error input and ii) Non zero error. This causes the output to accumulate. This saturation may lead to delay in response for change in input. This delay is increased if the saturation level is high.

VI.SIMULATION RESULT AND ANALYSIS

Using Matlab/simulink the DTC based induction motor drive simulations is validated. In simulation the motor specification is shown in Table 2.

Table 2 Induction Motor parameter

Power	149.2kW
Supply voltage	460V
Frequency	60Hz
Stator Resistance, R_s	0.01485Ω
Rotor Resistance, R_r	0.009295 Ω
Stator leakage Inductance, L_{ls}	0.0003027mH
Rotor leakage Inductance, L_{lr}	0.0003027 mH
Mutual Inductance, L_m	0.01046mH
Moment of Inertia, J	3.1Kg.m^2

A three phase supply of 460V, 60Hz is fed to DTC based IM drive is shown in Figure 5. Stator current, speed, torque and DC bus voltage are taken as output.

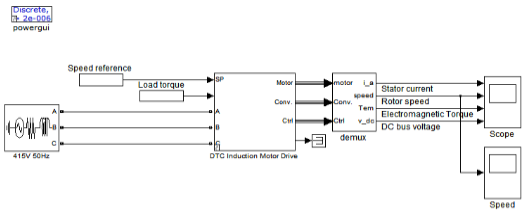

Figure 5 Overview of DTC method

A three phase supply is given to rectifier block to get DC output which is fed to inverter to get variable voltage supply. This supply is fed to induction motor and speed and torque are taken as output. Reference speed and actual speed are compared to generate reference torque is shown in Figure 6.

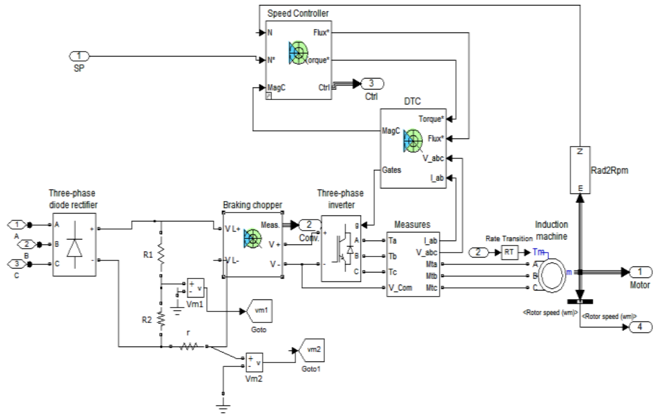

Figure 6 DTC simulink model

DC link current and voltage are used to produce actual torque and flux of IM. The actual values are compared with reference values and fed to Hysteresis controller to produce voltage vectors as shown in Figure 7.

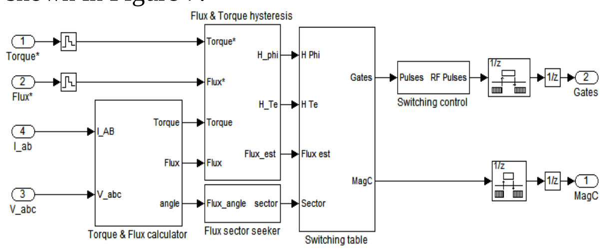

Figure 7 Mask of DTC

Actual speed is taken to calculate the reference flux. Actual speed and reference speed are compared using hybrid Fuzzy-PI controller to produce reference torque is shown in Figure 8. Using this controller only speed performance is improved. In order to minimize the torque ripple anti-windup PI controller is used.

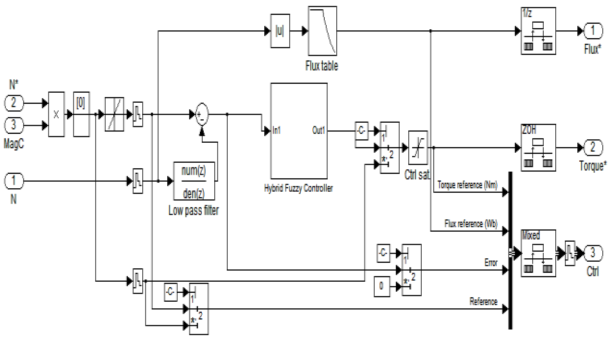

Figure 8 Mask of speed controller with hybrid Fuzzy-PI controller

Actual speed is taken to calculate the reference flux. Actual speed and reference speed are compared using anti-windup PI controller to produce reference torque is shown in Figure 9.

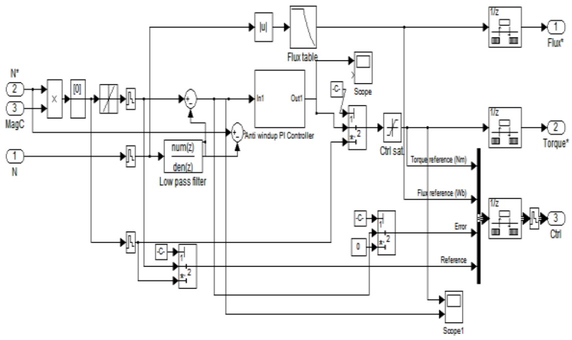

Figure 9 Mask of speed controller with Anti-windup PI controller

The simulation block for anti-windup PI controller is shown in the Figure 10. Using anti-windup PI controller speed performance is improved than the PI controller and also torque ripples are minimized while using this controller.

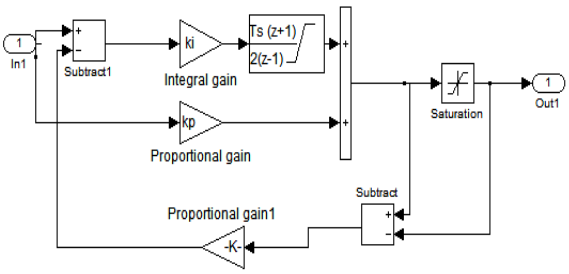

Figure 10 Anti-windup PI controller

The output of Stator current, rotor speed, torque and DC bus voltage are shown in Figures 11,12,13,14.

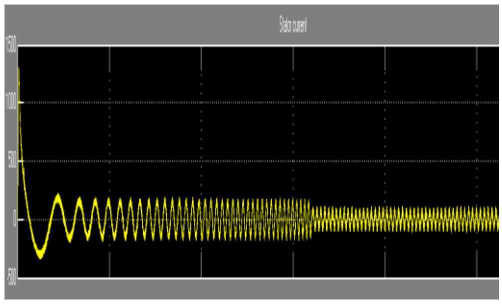

Figure 11 Output for Stator current

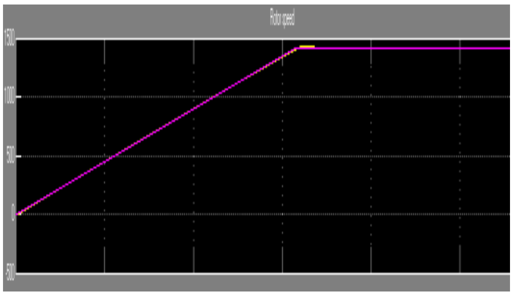

Figure 12 Output for Rotor Speed

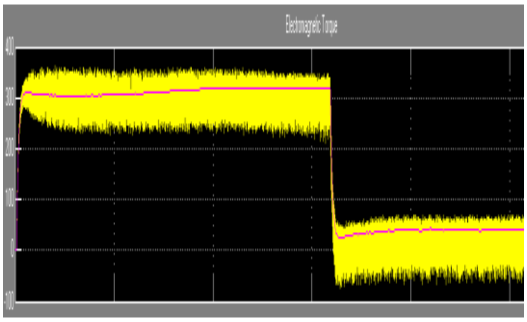

Figure 13 Output for Electromagnetic Torque

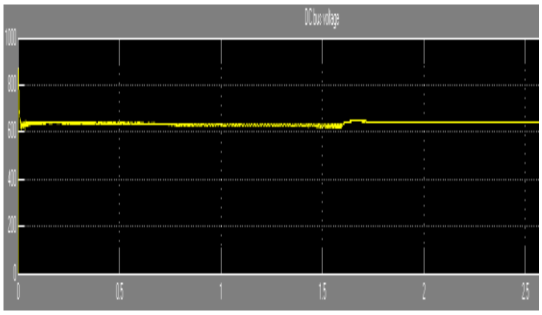

Figure 14 Output for DC bus voltage

The PI, hybrid Fuzzy-PI and Anti-windup PI controller is compared in this study and shown in the Table 3.

Table 3 Comparison of controller performances

Controller	Speed Over shoot (rpm)	Torque Ripples (Nm)	Performance
PI	9	27	Poor in both speed and torque
Hybrid Fuzzy-PI	5	27	Better in speed
Anti-windup PI	8	15	Better in speed and torque

VII.CONCLUSION

The DTC based induction motor drive is analyzed using the controller of hybrid fuzzy-PI and anti-windup PI controller. In conventional method single shunt resistor is used for the DTC algorithm. By using reconstruction method the cost can be reduced while implementing in hardware. In the proposed method the induction motor is rated at 149.2kW. In this method, using hybrid Fuzzy-PI speed performance is improved and anti-windup PI controller speed performance and torque ripple minimization are much better when compared to conventional DTC method.

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