Improvement of Flux Regulation with Adaptive PI Controller and DTHB based Direct Torque Control of Induction Machine

Gopala Venu Madhav, P. Sandhya Rani

Abstract*: *This paper presents an adaptive PI based two control strategies of Dynamic Hysteresis Torque Band (DHTB) for improving flux regulation at low speed and zero speed in lookup table based Direct Torque Control (DTC) of an Induction Machine (IM). This is achieved by varying the band value of torque dynamically but it is limited with flux error range. With the conventional HTB based DTC, at low and zero speed, the regulation of flux will not be good. To overcome this drawback, a small alteration in the structure is done, i.e., DTHB, thus retaining the simplicity of DTC algorithm. The performance is verified by varying the speed at low values. At low speeds of IM, the flux regulation and the speed is improved with adaptive PI controller based DHTB-II compared to DTC with DHTB-I and DHTB-II.

***Index Terms*: DTC, Adaptive PI Controller, DHTB-I, DHTB-II, Induction Machine.**

I. INTRODUCTION

The DTC of an induction motor has increased its popularity because of its simple control structure, excellent torque response and robustness against variations in parameters. The major demerits of the original DTC were high torque ripple [1], high sampling needs for digital implementation and droops in magnitude of flux at low speeds [2]. In order to solve these problems there are two groups of DTC variations are proposed [3], which are DTC with lookup table and other one is DTC without lookup table. In later method, a control algorithm is used for voltage vectors generation. Former method is also called as DTC-Space Vector Modulation (SVM), further two approaches are included in NLT-DTC, [4-6]. In this approach, SVM based synthesis is used to generate the voltage vectors. But the demerit of this approach is the control structure and implementation is complex. The second approach is the Predictive Torque Control (PTC) [7-10] in which the lookup table is not used for voltage vectors generation, instead predefined cost function is applied. But the high computation burden [10] and the total harmonic distortion are the demerits of the PTC techniques. For later method, appropriate control bandwidth ensures the proper operation; this requires the processor of high performance. Moreover, at no load conditions, this method has failed to operate at low speeds including zero speed operation.

In DTC with lookup table, voltage vectors are obtained from lookup table based on torque and flux requirements. Literatures [11-13] give different techniques involving large lookup tables with improved torque response, but high complex in nature. An alternative technique for the torque controller is the hysteresis band variation according to different speed profiles [14, 15]. The triangular signals of high frequency are injected into the torque errors, called dithering method [16, 17]. But the low speed performance of all these methods failed to operate. In [18], regulation of flux is utilized at low and even zero speed conditions for the improvement of state estimation at such speeds of a DTC drive. In [19], constant switching frequency control method is proposed, in which the torque response is not dynamically good compared to conventional one at regulated flux, this is because the torque hysteresis loop bandwidth is limited by the frequency of carrier wave (triangular), and at low speeds by this method adopted the reverse voltage vectors are chosen and because of this there is an increase in torque ripple also.

To avoid the above drawback, Dynamic Hysteresis Torque Band (DHTB) is necessary, i.e., during flux regulation failure and to reduce the ripple in torque over wide speed control range, the torque bandwidth has to be reduced. Therefore, to address these above said issues, the DTHB based DTC drive is introduced in this paper. In the proposed type of DHTB, reduction in harmonics of current and also ripple of torque and reverse voltage vectors selection is addressed by two sets of torque band, first one is based on the rated torque value of 10 to 15%, which gives the normal operation of the DTC drive [20, 21] and second one is the dynamically varying hysteresis torque band wherein reverse voltage vectors are selected properly and also it gives the necessary control when regulation of flux fails at low speeds. Thus, without modification in the structure of DTC, the drawback of regulation of flux at low speeds is addressed.

As proposed in [18], the presented DHTB based DTC drive have good dynamics of torque, and its torque band, good regulation of flux can be achieved at low speeds. The performance of the proposed DHTB control I verified by varying the speed at low values. The adaptive PI control based DHTB-II has better speed, torque and flux responses at low speeds compared to the DTC based on DHTB-I.

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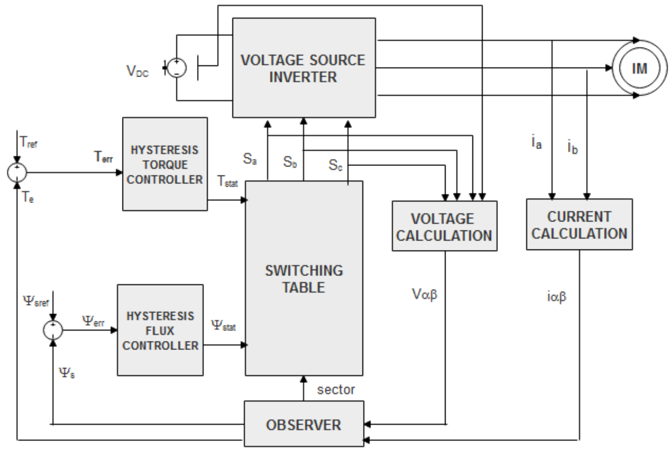

Fig.1: DTC of IM

II. DTC WITH LOOKUP TABLE

The Induction Machine (IM) dynamic modeling is described by the following equations in stationary reference frame:

$$\bar{v}_s^s = R_s \bar{\iota}_s^s + \frac{d\bar{\psi}_s^s}{dt} \quad (1)$$

$$0 = R_r i_r - j\omega_r \bar{\psi}_r + \frac{d\bar{\psi}_r}{dt} \quad (2)$$

$$\bar{\psi}_s = L_s \bar{I}_s + L_m \bar{I}_r \quad (3)$$

$$\bar{\psi}_r = L_r \bar{I}_r + L_m \bar{I}_r \quad (4)$$

$$T_{em} = \frac{3}{2} p \frac{L_m}{\sigma L_s L_r} |\bar{\psi}_s||\bar{\psi}_r| \sin \delta_{sr} \quad (5)$$

where, $\bar{I}_s$=stator current and $\bar{I}_r$=rotor current, $\bar{\psi}_s$=stator flux and $\bar{\psi}_r$ =rotor flux, ω_r =angular speed of rotor, $\bar{v}_s^s$ =stator voltage. R_s, R_r, L_s, L_r and L_m are stator and rotor parameters. $\sigma = 1 - L_m^2/L_s L_r$, p = pole pairs, and δ_{sr} = load angle.

Figure 1 (3), shows the DTC with conventional type lookup table. Table I shows the voltage vector selection, which is based on the torque (T_{stat}) and flux (ψ_{stat}) errors, if there is an increase in both the errors of flux and torque, the corresponding voltage vector selections is done in the form of zero (0), active forward (1), active reverse (-1), and zero (0) voltage vectors are selected as mentioned in Table I and the selection also depends on the position of $\bar{\psi}_s$, which is not shown.

TABLE I Voltage Vectors Selection

Ψ_{stat}	T_{stat}	Voltage Vector Selection	
↑	↓	Voltage Vector (Zero)	Voltage Vector (Active Reverse)
	↑	Voltage Vector (Active Forward)	

↓	↓	Voltage Vector (Zero)	Voltage Vector (Active Reverse)
	↑	Voltage Vector (Active Forward)	

↑=increase in value; ↓=decrease in value

III. PROPOSED DYNAMIC HYSTERESIS TORQUE BAND

Two types of dynamically varying torque band is proposed in this paper, first one is named as DHTB-I and the second one is named as DHTB-II. The regulation of the flux at low speeds is addressed by the proposed technique that means, the drooping of the flux at low speeds is avoided and also the voltage vectors (active reverse) effects can also be reduced. Torque hysteresis band is varied from $\Delta HB_{T_{e_1}}$ to $\Delta HB_{T_{e_2}}$ when there is failure of regulation of flux (stator).

A. DHTB-I

Figure 2 shows the proposed DHTB-I based DTC of IM, from the Fig. 2, the observer gives the speed of rotor and it is compared with reference value which is utilized in proposed DHTB-I generation. Based on the low value of speed of rotor, the activation of $\Delta HB_{T_{e_2}}$ is done. The value of speed (threshold) at which $\Delta HB_{T_{e_2}}$ is activated can be calculated theoretically by analyzing the simulations of Fig. 3, wherein by knowing the drooping of stator flux (critical value). The critical value of this flux in terms of flux critical point is determined by (6) for the HTBs selection and simplification of these HTBs selection is limited by critical value of flux error.

$$\bar{\psi}_c = k\left(|\bar{\psi}_s|_{ref}\right) \quad (6)$$

where $|\bar{\psi}_s|_{ref}$ =reference flux magnitude, $\bar{\psi}_c$ =flux point (critical) and k =weighting factor (0< k< 1). $\bar{\psi}_{err}$ (error of flux) < E_c (error of flux at critical condition) and is given by (7):

$$E_c = |\bar{\psi}_s|_{ref} - \bar{\psi}_c \quad (7)$$

Unnecessary activation of $\Delta HB_{T_{e_2}}$ during the condition of IM running at greater than low speeds can be avoided by proper selection of k value. The critical point of flux increases and decreases accordingly, when the value of k increases and decreases, respectively, resulting in the avoidance degradation of flux in large and large drooping of flux (before activation of $\Delta HB_{T_{e_2}}$ is done) respectively. A method of trial and error is used for k , as determination of k is a problematic, proper value of k is required for $\Delta HB_{T_{e_2}}$ selection and to ensure the same. In this paper, $\bar{\psi}_c$ =0.9063Wb, E_c =0.0477Wb, and k =0.95 is set and as discussed above, it is considered that with the variation of k, the regulation of flux is degraded.

The speed (critical value) is varied along with the variation of parameters of IM and also mechanical load of DTC drive. Taking an example, the torque slope (negative) is low extremely during no-load condition of DTC of IM, which is the worst condition of the drive, which increases the possibility of $\Delta\psi_{s1} < \Delta\psi_{s2}$, as the vector voltage (zero) application increases in duration. Hence, (8) gives the condition of the DHTB-I operation.

$$HTB = \Delta HB_{T_{e1}}, for\ |\omega_r| > \left|\omega_{r_{\psi c}}\right|$$
$$HTB = \Delta HB_{T_{e2}}, for\ |\omega_r| \leq \left|\omega_{r_{\psi c}}\right| \qquad (8)$$

where $\omega_{r_{\psi c}}$ =critical speed (threshold) w.r.t. flux (critical point). $\omega_{r_{\psi c}} \approx 12$ rad/s is chosen in this paper based on simulations of Fig. 2.

B. DHTB-II

Figure 3 clearly shows that the observer output doesn't contain the speed of IM, instead the $\Delta HB_{T_{e2}}$ is activated by ψ_{error} i.e., difference of reference and estimated fluxes. This is major advantage of the DTHB-II technique compared to DHTB-I. The equation used for the determination of DHTB-II operation condition is given by (9).

$$HTB = \Delta HB_{T_{e1}}, for\ |\psi_{error}| < |E_c|$$
$$HTB = \Delta HB_{T_{e2}}, for\ |\psi_{error}| \geq |E_c| \qquad (9)$$

Figure 4 shows the variation of flux and torque hysteresis bands with the proposed method (as an example it is illustrated). The importance of he variation of these bands is to adjust the flux and torque depending on the necessity to control the DTC drive performance. Quick reduction in torque value can be obtained by properly selecting the $\Delta HB_{T_{e2}}$, which in turns is useful for the production proper voltage vector (reverse), this criteria will either lead to reduction of time of voltage vector (zero) application or may lead to production of overshoot in torque response as shown in Fig. 3. $\Delta HB_{T_{e1}}$ and $\Delta HB_{T_{e2}}$ switching (high frequency) is being limited by given sampling frequency of DTC drive.

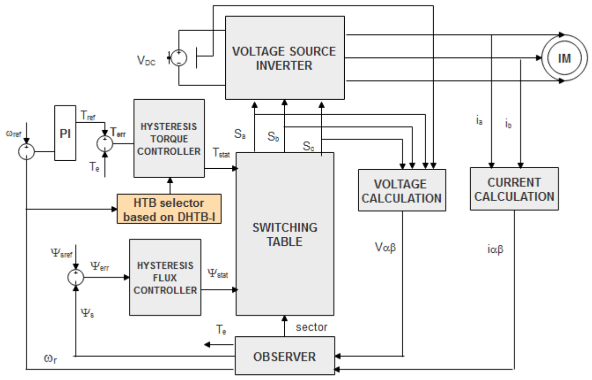

Fig.2: Proposed DHTB-I based DTC of IM

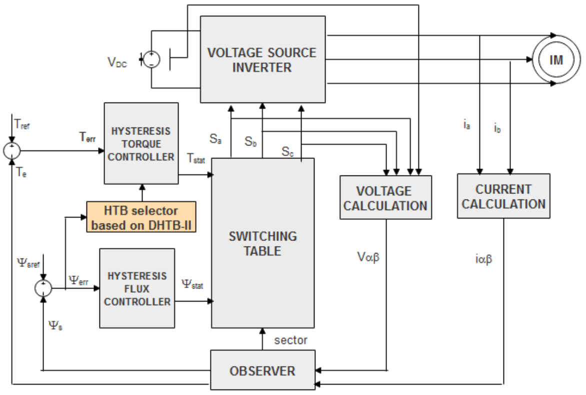

Fig. 3: Proposed DHTB-II based DTC of IM

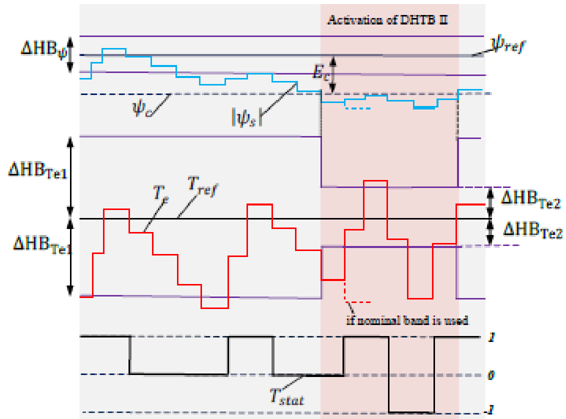

Fig. 4: Flux, torque, and torque status discretized waveforms with proposed DHTB-II method based DTC of IM.

The voltage vector selection is similar as explained in Section II with Table I, here, it depends on the threshold value of regulation of flux.

IV. RESULTS AND DISCUSSION

Table II lists the system parameters and HTB values. Non-linearities of inverter are not considered in the simulation due to effect of dead-time and dynamics of complete DTC drive.

The results are obtained for step change in the speed from 22rad/s initially to 10rad/s at 0.5s. From the Fig.s 5, 6, and 7, it is observed that the torque is having high ripple for DTC with HTB, and it is less for both the proposed DHTB-I and II techniques. The flux response is deteriorated for DTC with lookup table (conventional one), which indicates that the regulation of flux is not in control for DTC drive at low speeds because of fixed value of the HTB ($\Delta HB_{T_{e1}}$) and not the dynamic value which can restore the deterioration of regulation of flux, compared to the proposed DHTB-I and II, the regulation of flux is obtained at low speeds. Compared to the DHTB-I based DTC, the proposed adaptive PI controller based DHTB-II technique outperforms in all respects, i.e., the speed response is good, even during the step change, the torque response has less ripple and he flux response has also less ripple and also the regulation of the flux is good indeed.

TABLE II Parameters of IM and HTB values

IM	
Power (Rated)	1500W
Voltage (Rated)	400V
Current (Rated)	3.7A
Speed (Rated)	1430rpm
Efficiency	82.8%
p.f.	0.72
Rs	3.0Ω
Rr	4.1 Ω
Ls	341.9Mh
Lr	351.3mH
Lm	324.0mH
P	2
HTB Values	
HTB (Nominal)	1N-m
HTB (Reduced)	0.045N-m
Flux HB	0.025Wb
Torque (Rated)	9N-m
Stator Flux (Rated)	0.954Wb

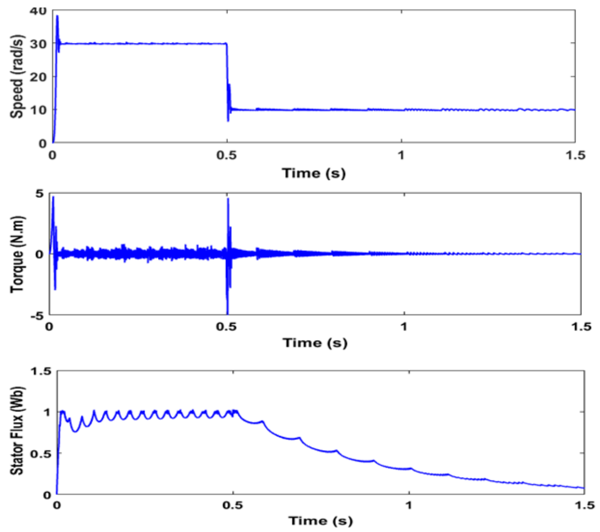

Fig.5: Results of IM for DTC with conventional lookup table

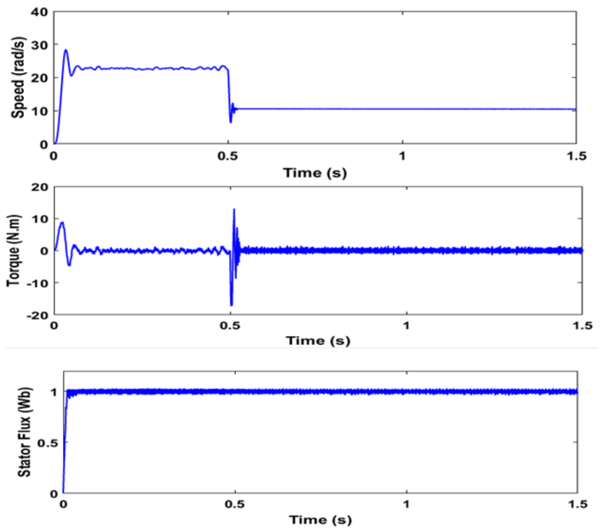

Fig. 6: Results of IM for DTC with proposed DHTB-I

When the HTB is set to 1N-m (nominal value), it means that $\Delta HB_{T_{e_1}}$ is selected and if HTB is set to 0.045N-m (reduced value), it means that $\Delta HB_{T_{e_2}}$ is selected for low values of speed (speed of DTC drive reaching 10rad/s), and it is shown clearly in Table II. $\Delta HB_{T_{e_2}}$, once it is selected means, it results in choosing of appropriate voltage vectors (Active forward and Active reverse) and the switching frequency of voltage is less with the proposed technique, which enhances the efficiency of DTC drive.

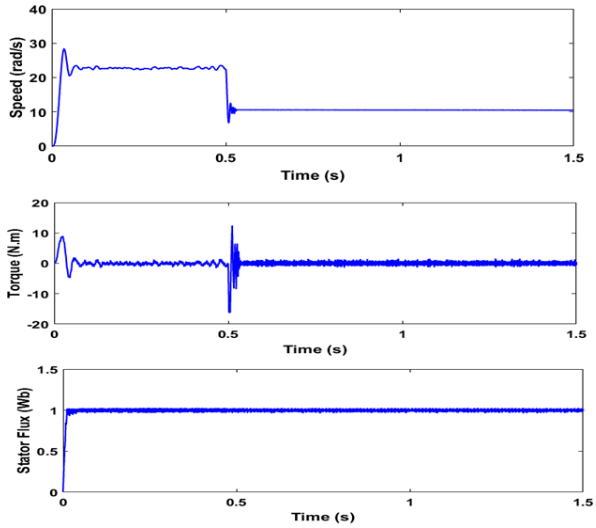

Fig.7: Results of IM for DTC with proposed DHTB-II

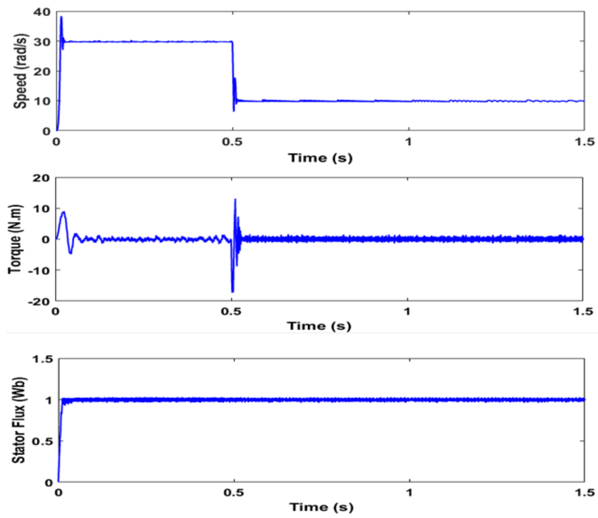

Fig. 8: Results of IM for DTC with Adaptive PI Controller based DHTB-II

V. CONCLUSIONS

This paper proposed an adaptive PI controller based Dynamic Hysteresis Torque Band (DHTB) fed IM drive for improvement of regulation of flux during low speeds. The dynamically varied torque band is classified as DHTB-I and DTHB-II. The performance of adaptive based PI controller based DHTB-II is compared with the DTC based on DHTB-I and DTHB-II and the results clearly shows that the regulation of flux is improved, the dynamics of the torque and speed responses are good comparatively with DHTB-I and DTHB-II based DTC drive. For all these to achieve there is no requirement of any change in the structure of DTC, hence it is simple in implementation. MATLab/Simulink software is used for simulation and the results validate the efficiency of proposed scheme and even DTHB-I and II.

We can replace adaptive PI Controller with Intelligent control techniques like Fuzzy logic controller and ANN (Artificial Neural Networks) to get more accurate and better speed and torque step responses.

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