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A Novel Procedure for Torque Ripple Minimization of an Induction Motor

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***Abstract*—In the paper, a simplified strategy for the immediate torque control (ITC) of an induction motor is proposed, which beats the inconvenience of high torque ripple tormenting the customary ITC method. With this, the inverter voltage vector chose from the switching table is exercised for the time interim required by the torque to achieve the upper (or the lower) limit of the band, where the time interim is ascertained from a reasonable modeling of the torque dynamics. It is appeared by exploratory outcomes that the system yields an extensive diminishment of the torque ripple. The result is that the torque ripple of the induction motor is compelled inside the hysteresis band of the torque controller, for a band of standard esteem. Under this situation, an augmentation of the method is created, which helps keep the torque ripple at least. To survey the qualities of the proposed DTC procedure, the accompanying amounts: normal torque error, rms estimation of the torque ripple, and inverter switching frequency are measured for various stator flux angular speed and hysteresis groups of the torque and flux controllers. The simulations are carried out in MATLAB environment.**

***Index Terms*— hysteresis controller immediate torque control (ITC), induction motor (IM) drives, RMS estimation, torque ripple reduction.**

I. INTRODUCTION

In previous years, immediate torque control (ITC) has turned out to be an effective strategy for controlling induction motors (IMs) in light of its quick conduct (because of the closed-loop control of the motor flux and torque by hysteresis controllers), its basic structure (because of the absence of current loops and shaft sensor), and its strength (because of the utilization of the stator resistance just in the control calculation) [19]-[21]. The utilization of a similar voltage order for the entire examining period causes a torque ripple, which in steady state is substantially more prominent than the standard band utilized for the hysteresis torque controller.

This paper implements a simple technique for the direct torque control (DTC) of an induction motor which overcomes the trouble of high torque ripple afflicting the conventional DTC technique, this technique is quite simple and is appropriate for modern DSPs [1]. In [2], the author proposes a continuous variant of the DTC which is obtained by replacing the discrete controller's specific to the classical DTC with two or three continuous controllers. A new technique namely Sector Advancing Technique (SAT) for reducing the response time of the drive for a known torque command. Simulation studies are carried out in MATLAB environment and results of DTC with SAT over conventional DTC are presented in [3]. The main aim is to provide a decoupled control of torque and flux. The main demerit associated with the conventional DTC was the high torque, flux ripples and variable switching frequency of the devices which was rectified by utilizing space vector modulation (SVM) technique [4].

Direct torque control based constant Volt/Hertz technique was the effortless speed control method for the three phase induction motor drives. This method uses the stator flux and torque error to generate the stator voltage and frequency reference for controlling the induction motor [5]. Various aspects related to controlling induction motors are investigated along with it different control strategies are explored. The direct torque control (DTC) strategy is studied in details and its relation to space vector modulation (SVM) is emphasized [6]. A DTC model has been developed and tested using a MATLAB package [7]. A modular approach for Simulink implementation of induction machine in arbitrary reference frame is described in stepped manner. After implementation, model performance is represented in stator, rotor and synchronous reference frame [8]. In order to improve the performance of DTC at low speed and reduce switching frequency at high speed, a method that uses circular flux control model when the measured speed is no more than 10% of the rated speed and hexagonal model at higher speed is represented. Simulation based on this method is given on the platform of MATLAB [9].

Improved high speed Induction Motor (IM) torque control algorithm that achieves full inverter voltage utilization in field weakening and smooth speed transition from the base speed to high speed region is presented [10]. In [11], the author describes DTC of induction motor with a constant switching frequency torque controller. By this method constant switching frequency operation can be achieved for the inverter along with it, the torque and flux ripple will get reduced. In [12], the author deals with the synthesis and implementation of a novel direct torque control (DTC) strategy dedicated to the control of BLDC motor drives. 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 [13].

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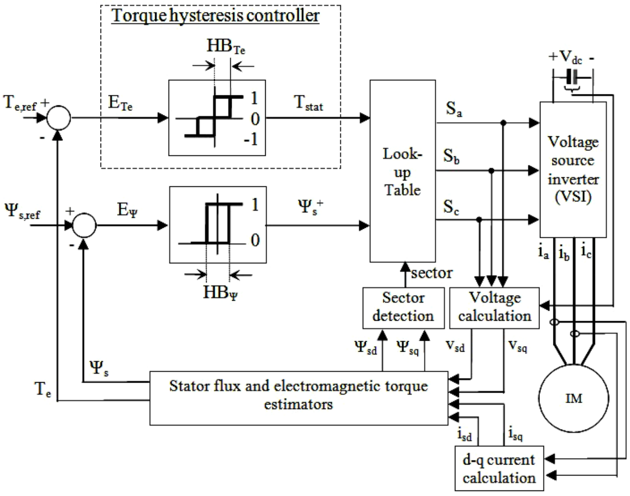

Fig.1 Block diagram of Principle of ITC

Direct torque control technique of induction motor can be used with different controlling techniques which includes Proportional controller, Proportional Integral controller, Fuzzy Logic controller, Neural Network and Space Vector Modulation [14]. The author have analyzed design of space vector modulation based direct torque controlled (DTC-SVM) five-phase induction motor incorporated with ANN controller and has given a comparison with PI controller. This controller is employed to improve control performance parameters like torque & flux ripple, settling and rise time when compared to that of PI controller [15]. In the sensor-less direct torque control (DTC) drive system of permanent magnet brushless dc motor (BLDCM), the estimations of instantaneous electromagnetic torque and stator flux linkage are two key issues [16]. A simplified current minimization technique for direct torque controlled IPM drives is proposed by utilizing a normalized look up table that is independent of motor parameters [17]. Implementation of multi-rate sampling technique for carrier space vector pulse width modulation based direct torque control (CSVPWM DTC) of induction motor (IM) drive with an objective to reduce the electromagnetic torque ripple is explained [18].

In detail, the paper is composed as follows. Segment I describes introduction, Segment II presents Basics about direct torque control, Segment III delineates the torque ripple phenomena and infers a helpful portrayal of the torque dynamics in a stator flux situated frame. Segment IV clarifies the control calculation created to compel the torque ripple inside the standard band of the hysteresis controller and archives the impressive decrease accomplished in the torque ripple by exploratory tests. The motor torque, in any case, still exceeds the cutoff points postured by the hysteresis bands in the light of the delay inborn in the discrete-time operation of the control framework.

To beat the burden, a repaying activity is orchestrated, which depends on the expectation of the motor torque one testing period ahead, as clarified in Segment V. This further arrangement lessens much more torque ripple and keeps it completely inside the band limits. A while later, the method is stretched out to agree to a hysteresis torque controller having thin or zero band. In Segment VI, the qualities of the proposed method are measured and contrasted with those of the regular ITC strategy. In detail, the normal torque error, the RMS estimation of the torque ripple and the inverter switching frequency are resolved for various estimations of the stator flux angular speed and hysteresis groups of both the torque and the flux controller.

The experimental results included in the paper are carried out on the setup specified in the Appendix.

II. DTC BASICS

Detailed block diagram of principle of ITC is represented in figure-1. It works as follow: the values of stator flux and torque references $T_{s,ref}, \tau_{ref}$ are contrasted with the genuine esteems acquired by the estimator ES. Values of resultant errors e_T, e_τ are inputted into the hysteresis flux and torque controllers FC and TC, which produce the digitalized voltage demands $v_{T,dem}, v_{\tau,dem}$, required to drive the IM stator flux and torque inside the bands of the individual controllers.

In view of the voltage demands and the sextant where the stator flux vector is situated, a fitting inverter voltage vector is chosen from the switching table ST. With the regular ITC strategy, it is exercised to the motor for the entire examining period. Fig.2 demonstrates the inverter voltage vectors and the flux sextants in α, β stationary frame with the axis adjusted along the axis a_s of the phase 'a' of the stator. For the stator flux vector in sextant 1, the switching table is accounted for in Table I. At the point when the stator flux vector is situated in different sextants, the table changes appropriately. The factors S_a, S_b, S_c in figure-1 are the conditions of the upper switches of the inverter and rely upon the chose inverter voltage vector. Together with the dc-link voltage (V_{dc}) and the stator currents i_{as}, i_{bs} they are inputted into the block ES to estimate value and sextant of the stator flux vector, and motor torque.

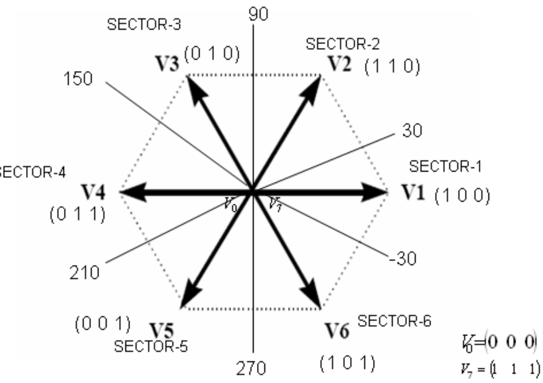

Fig.2 Inverter Switching States

Table. I Switching table

$V_{T,dem}, V_{\tau,dem}$	1,1	-1,1	Any,0	1,-1	-1,-1
Inverter Voltage Vector	V_2	V_3	V_0,V_7	V_6	V_5

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Let the motor pivot into the anticlockwise way. In steady-state condition, the torque error lays on the upper half-cycle of the hysteresis torque controller and the relevant arrangement of the inverter voltage vectors is made out of the dynamic vectors $\tilde{V}_2, \tilde{V}_3$ to expand the torque of the zero vectors $\tilde{V}_0, \tilde{V}_7$ and to diminish it.

III. TORQUE RIPPLE AND MATHEMATICAL FORMULATIONS

The conduct of an induction motor controlled with ITC is advantageously broke down within the (d,q)synchronous frame having the axis-d settled to the stator flux vector. The d,q projections of $\tilde{V}_2$ and $\tilde{V}_3$ are:

$$\begin{cases} V_{di} = 0.667 \times V_{dc}\cos(\emptyset_i - \emptyset_T) \\ V_{qi} = 0.667 \times V_{dc}\cos(\emptyset_i - \emptyset_T)' \end{cases} i = 2,3 \qquad (1)$$

where $\emptyset$ = angle of inverter voltage vector to α_s which can be dictated just as:

$$\emptyset_i = (i-1) \times \frac{\pi}{3}, i = 2,3 \qquad (2)$$

where $\emptyset_T$ = angle of stator flux vector to α_s. Obviously, the (d, q)projections of $\tilde{V}_0$ and $\tilde{V}_7$ are of zeroth value.

For a ITC conspire amidst stator flux managed towards optimum esteem, variation in torque amid the testing time frame is figured out. Here, the streamlined articulation found in is utilized as:

$$\Delta_\tau = 1.5 \times pT_{sN}\Delta i_{qs} + \frac{\tau}{T_{sN}}\Delta T_s \qquad (3)$$

Where Δ_T = variation in torque,
p = pole-pairs,
T_{sN} = optimum significance of stator flux,
Δi_{qs} = difference in the axis-current.

Formulae (3) could be promptly achieved in distinction to torque condition represented within this picked outline

$$\tau = 1.5 \times pT_s i_{qs} \qquad (4)$$

Near to the optimum stator flux, variation in torque endure to be

$$\Delta_\tau = (1.5 \times pT_s)\big|_{T_{sN}} + (1.5 \times pi_{qs})\big|_{T_{sN}}\Delta T_s \qquad (5)$$

By formulae (4), the value written as

$$1.5 \times pi_{qs} = \frac{\tau}{T_{sN}} \qquad (6)$$

and its substitution into formulae(5) yields formulae(3).
The term in (3) can be communicated as

$$\Delta i_{qs} = \frac{V_{qi} - e_s - R_s i_{qs}}{\sigma L_s} t_{ITC} \qquad (7)$$

Here, the R_s = stator resistance,
t_{ITC} = examining time frame,
σL_s = aggregate spillage inductance of induction motor.

Where, (7) is revamped as an element of a nonexclusive rather than t_{ITC}.

The back-emf e_s of the induction motor is given by

$$e_s = \omega_T T_{sN} \qquad (8)$$

Here, the value ω_T = angular speed relative to stator flux. Also, the variation in flux could endure to be:

$$\Delta T_s = (V_{di} - R_s i_{ds})t_{ITC} \qquad (9)$$

By above equations, we have observed that torque as well as the variation in flux are directly corresponding prior to examining time frame. The progressions, detailed in process of the optimum torque τ_N, have being huge clarifying huge variation in torque showed by way of regular ITC method. Obviously, a lower estimation of t_{ITC} would decrease the progressions however feel necessity for an augmented effective processor. In distinction to normal reliance on torque variation on $\emptyset_T$ because of formulae(1). Specifically at immense speeds, the expansion of the back-emf adjusts considerably as the variation in torque value as for the lesser-speed conveyance.

Dislike variation in torque, variation in flux doesn't inhabit impact by the stator flux angular speed moreover next to no aside load. Every one of these impacts are legitimately displayed by formulae (3),(7) and (9).

IV. BAND-CONSTRAINED TECHNIQUE

Point of this simplified procedure is keep up value of the torque variation inside the hysteresis band of the torque controller paying little respect to the working point by applying the inverter voltage vector chose from the switching table for a proper time-duration. For advancing the time-duration, various formulas are used, since the term $\frac{\tau}{T_{sN}}\Delta T_s$ and the protection voltage drop don't contribute considerably to the torque variations, they will be from now on slighted with the reason for lightening the calculation endeavors.

The angular speed prior to the stator flux is vital for determining the back-emf which is drawn from the block ES in Fig.1 with the help of methods for the accession depicted in other strategies. There are two different cases for controlling the value of the torque:

1) The first case is amid the torque of the motor is underneath the major restrict and the torque degree is positive and the torque advances towards the major restrict.
2) The second case is amid the torque of the motor is over the minor band restrict and the torque degree is negative and the torque advances towards the minor restrict. Both the conditions will be managed independently.

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A. Major Limit Constraint

In the first case, the inverter voltage vector is chosen among two dynamic vectors as indicated by the flux demand. The increase in the torque esteem is important to achieve the major band limit is

$$\Delta\tau_u = \tau_{ref} + h_\tau - \tau. \qquad (10)$$

With the values in (3) and (7), the time-duration t_u needed to build up the value of the torque is

$$t_u = \frac{\sigma L_s}{1.5\times pT_{sN}(V_{qi}-e_s)}\Delta\tau_u. \qquad (11)$$

t_u Relies upon the angle enclosed by the dynamic voltage and stator flux vectors, and angular speed of the stator flux. In this event that $t_u > t_{ITC}$, the dynamic voltage vector is exercised considering the entire inspecting period. Else, being exercised just for (11), when a zero voltage vector is exercised as long as the rest of the interim of the testing time frame. At the point when $V_{qi} < e_s$, the chose dynamic voltage vector diminishes the torque as opposed to expanding torque. Along these lines, the control calculation alters the choice derived from table.1 which is applied to induction motor. This abstains from changing excessively the stator transition greatness the other way of the control demand.

B. minor Limit Constraint

In the second case, a zero inverter voltage vector is exercised to induction motor. The decrease in the value of the torque is important for achieving lower band limit is

$$\Delta\tau_l = \tau_{ref} + h_\tau - \tau \qquad (12)$$

Where $\Delta\tau_l$brings about a negative amount. From (3) and (7), the time-duration t_l needed for the induction motor to build up the value of the torque $\Delta\tau_l$ is

$$t_l = \frac{\sigma L_s}{1.5\times pT_{sN}e_s}\Delta\tau_l. \qquad (13)$$

t_l relies upon the angular speed of the stator flux only. In the event that $t_l > t_{ITC}$, the zero voltage vector is exercised prior to the entire inspecting time-duration. Else, being exercised just for while a dynamic voltage vector is exercised as long as the rest of interim of examining time frame.

C. Limit Band Case

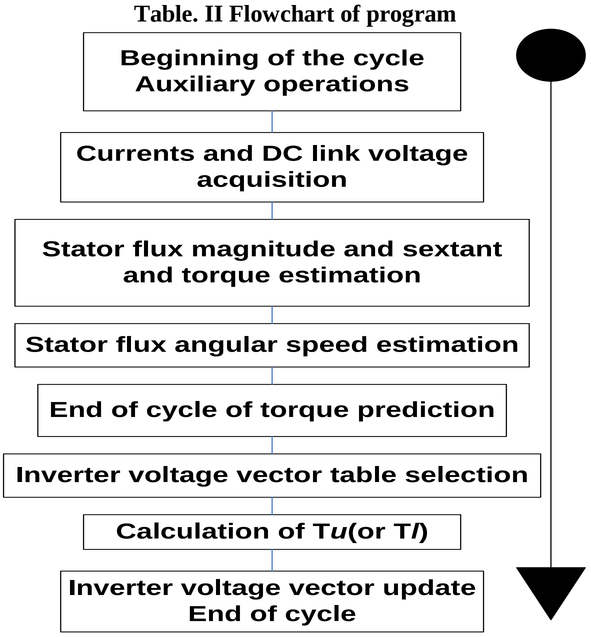
Consider the first case & assume period interim $t_u < t_{ITC}$ is computed by (11), which requires the use of a dynamic voltage vector for t_u. In case that hysteresis band of the torque controller is narrow to use of a zero voltage vector in the rest of time interim of the inspecting time frame i.e., in $(t_{ITC} - t_u)$ exerts the value off the torque beneath the minor restrict, the overhead calculation does not commission and, consequently, is to be broadened. This is achieved by leaving the torque allowed to go above major restrict and ascertaining the use of interim of the dynamic voltage vector all together considering the progressive activity of the zeroth voltage vector, the value of the torque compares the associative incentive towards finish about inspecting time frame. Relative control technique is figured on the point of:

$$\Delta\tau'_u = \tau_{ref} + h'_\tau - \tau(0) \qquad (14)$$

$$t'_u = \frac{1.5\times pT_{sN}(V_{qi}-e_s)}{\sigma L_s}\Delta t'_u. \qquad (15)$$

$$\Delta\tau'_l = \tau_{ref} - \tau(t'_u) \qquad (16)$$

Table. II Flowchart of program



$$\Delta\tau'_l = \frac{1.5\times pT_{sN}(V_{qi}-e_s)}{\sigma L_s}(t_{ITC} - t'_u) \qquad (17)$$

$$\Delta\tau'_u + \Delta\tau'_l = \tau_{ref} - \tau(0) \qquad (18)$$

where $\tau(0)$ and $\tau(t'_u)$ are the torque esteems toward the start of the examining time frame and at the time interim t'_u, separately, and the superscript means amounts identified with an invented hysteresis band within major restrict $h'_\tau > h_\tau$ and with the minor restrict which is equivalent directed towards zero. Representing the values of (15) and (17) into (18), the use of interim of the dynamic voltage vector is ascertained as:

$$t'_u = \frac{1}{V_{qi}}\left\{\frac{\sigma L_s}{1.5\times pT_{sN}}\left[\tau_{ref} - \tau(0)\right] + e_s t_{ITC}\right\} \qquad (19)$$

The contrast between t_{ITC} and t'_u yields pertinence interim of the zeroth voltage vector. A double system could be created for the second case. With the use of this technique, disturbance in the value of the torque is minimized reasonably as expected and, moreover, it is focused on the torque reference.

D. Exploratory Results

Simplified ITC strategy is experimented relative to similar conditions from regular method. Torque of the induction motor is framed in figure-3. We have observed a generous decrease in disturbance of the torque value. In spite of the change, the limits in which the value has to be varied exceeds

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the nominal value of the limit. This is because respective handling delay from the collection of data sources to the moment of utilization of the distinct voltage vector. Meanwhile, the value of the torque is altered and activity does not coordinate with the refreshed value of the torque esteem. The delay is equivalent to around one examining period as the data sources are procured a short time after the start of inspecting time frame although the distinct inverter voltage vector is exercised exactly towards finish of the testing time frame.

V. TORQUE PREDICTION

To dispense with the remaining over-abundance related to the disturbance in the value of torque variation, torque of the motor is anticipated towards relative finish of the time duration and voltage vector of the inverter is chosen in premise of anticipated torque value. The Step-wise procedure of Table.II points the interests of the flowchart calculation. Relative conditions of the inverter switches are excluded from achieved accounts due to the inner factors of the framework.

Inclusion of the prediction calculation in the band-compelled ITC method creates the torque ripple which is all around kept inside the hysteresis band of the torque controller. The comparing stator current of an motor phase and stator fluxes along the, α, β axes are confirmation of the little distortion of the current waveform and the great control of the stator flux accomplished with the proposed system.

VI. PERFORMANCE ANALYSIS

Considering the total appraisal procedure attributes, the normal torque error, RMS estimation of the disturbance in torque, and switching frequency of inverter is calculated for various flux angular speeds prior to stator.

Outcomes of proposed system affirm that this system incredibly enhances torque in steady-state execution of ITC plan.

Fig.3 to 12 are the graphs for conventional immediate torque control of induction Motor at 20% WN as shown:

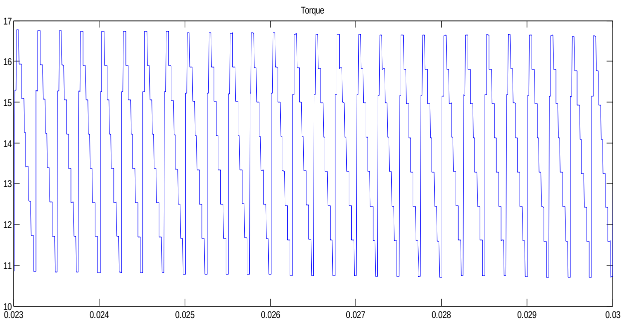

Fig.3 Torque variation w.r.t time

Variation in torque of the simplified ITC strategy contained ample magnitude of high frequency disturbances and it reflected in current waveform also. By observing the waveform results in Fig.3, the torque and current ripples have been reduced from 50% to about 11%.

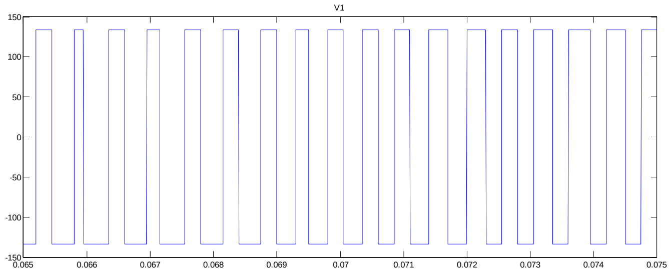

Fig.4 Applied phase voltage a w.r.t time

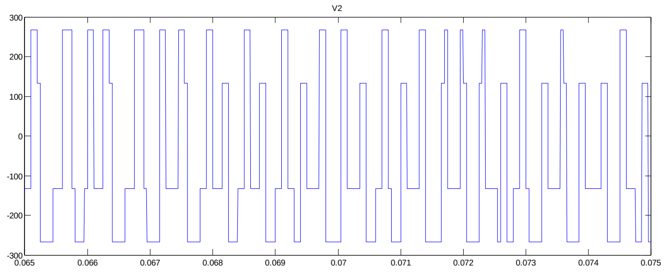

Fig.5 Applied phase voltage b of the induction motor

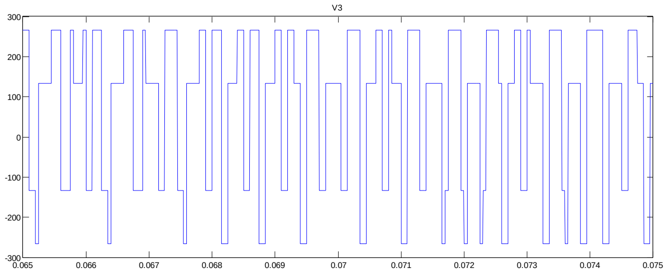

Fig.6 Applied phase voltage c of the induction motor

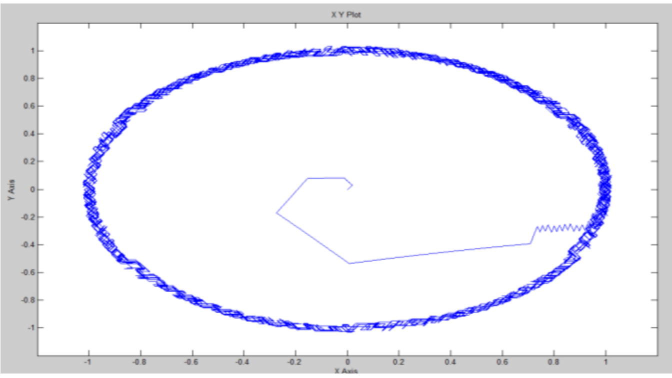

Fig.7 Hexagonal stator flux locus

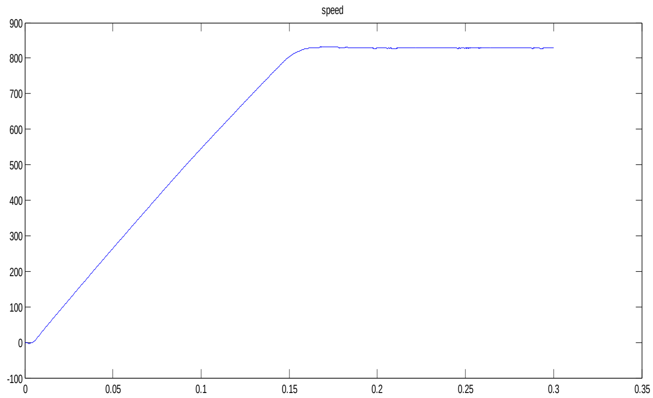

Fig.8 Speed variation of the induction motor

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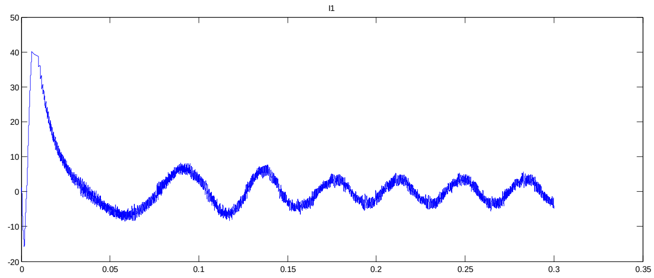

Fig.9 Stator current a of the induction motor

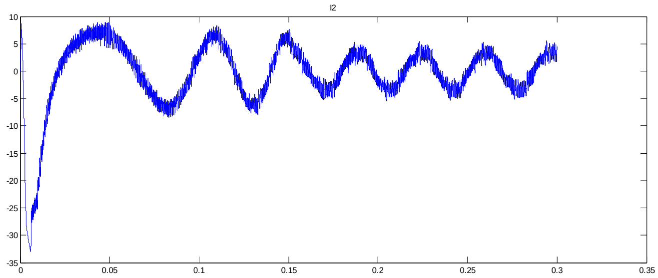

Fig.10 Stator current b of the induction motor

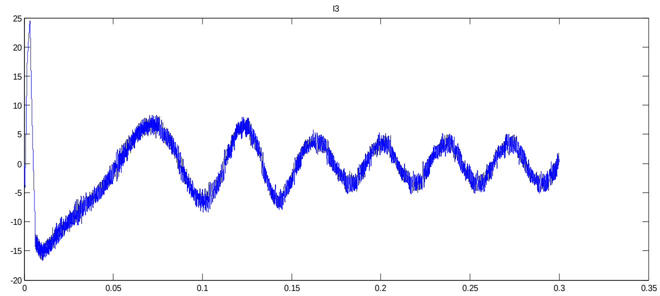

Fig.11 Stator current c of the induction motor

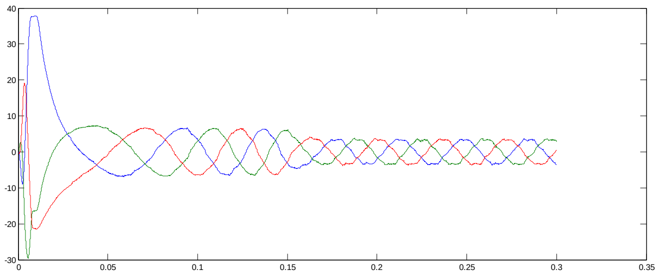

Fig.12 Stator current 3-phase of the induction motor

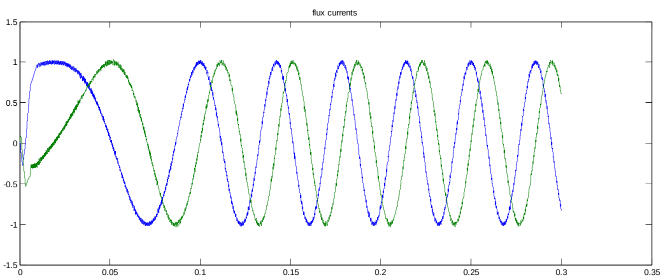

Fig.13 Flux currents w.r.t stator current

However, the outcomes are agreeable to the band-compelled ITC system in light of the fact that the after-effect switching frequency of customary method is excessively unassuming as long as the recompense limits of the cutting edge low-and medium-control power-electronic gadgets.

At long last, the RMS estimation of disturbance in torque variation and the frequency of switching of the inverter is observed and analyzed at a large portion of the ostensible estimation of flux angular speed prior to the stator which ends up diminishing estimations of hysteresis bands of the torque controller. For the zeroth hysteresis band, disturbance in torque value is directed by duration of testing time frame as this method accommodates one-time switching of the voltage vector of inverter in each inspecting time duration. Consequently, switching frequency prior to inverter ends up noticeably 33% of the reverse of the testing time frame at the same time.

VII. CONCLUSION

The strategy diminishes to the full degree the torque ripple tormenting the regular ITC plans, reliably with the testing time frame being used. The idea behind using this strategy is by implementing the selected voltage vector of inverter from the table.1 for the necessary time interim period for the torque to achieve upper band limit. By achieving the mentioned guideline, the torque ripple will be reduced as per the requirement. Prior to the zeroth-band limit, the procedure promptly reached out by presenting invented fictitious band limits. The algorithmic calculation prior to ITC method is very basic and appropriate for present day DSPs. But, it requires the extra learning of aggregate spillage inductance of motor. Be that as it may, the major role by this parameter for the accomplishment of the system isn't basic and a rough learning of it is satisfactory.

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APPENDIX

Information and values of the Induction motor used in the proposed technique are represented in Table.III. The V_{dc} -inverter supplying the induction motor is 353.33 V.

Table.III Data and parameters of Induction motor

Specific Parameter	Value
H.P.	2.68
P[kW]	2
freq[Hz]	50
L_r[mH]	190
L_m[mH]	187
L_s[mH]	192
R_s[Ω]	1.56
R_r[Ω]	1.37
σL_s[mH]	11
T_{sN} [Wb]	0.79
Nn[min^{-1}]	950
I_n[A]	4.866
U_n[V]	253.33
V_{dc}[V]	353.33