MINIMIZATION OF TORQUE RIPPLE FOR DTC-CSI FED INDUCTION MOTOR DRIVES DURING LOW SPEED OPERATION

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Abstract: *A novel MRAS based torque estimator is proposed in this paper to improve the dynamic performance and reduce the torque ripple of direct torque current source inverter (DTC – CSI) fed induction motor drive (IMD) at low speed operation. A direct torque control method allows usage of zero speed at nominal torque. In DTC, stator or rotor flux significantly used to estimate the electromagnetic torque. At low speed regions, mismatch between the stator resistance and its set value, stator flux cannot be effectively established and make torque ripples, results the performance of DTC controller degrades the system. A modified MRAS based speed and torque estimation technique overcome this problem and makes a system with good dynamic performance. The performance of this control method has been demonstrated using software package, MATLAB / SIMULINK and verified experimentally with a digital signal processor. The results prove that torque ripple has been reduced with an improving dynamic response.*

Key words: *Current Source Inverter, Induction motor drive, Direct Torque Control, MRAS based Torque Controller*

1. Introduction

Induction motor drive widely used in industry due to its simple construction, high efficiency, easy operation and less maintenance compare with DC motor, and extended to operate high power medium voltage drives. Current-source inverter is (CSI) (Figure.1) more suitable for medium-voltage drives applications [1]-[2] due to simple converter structure, motor-friendly waveforms, inherent four-quadrant operation capability, and reliable short-circuit protection. In high-power current-source inverter drives, the performance was improved by using different control strategies, PWM schemes, topologies, and efficiency [4]-[10]. The direct torque control [11] method introducing last three decades it provides very quick and precise torque control and fast dynamic response. The DTC is based on decoupled control of flux and torque. DTC – CSI fed induction motor drive involves the direct control of flux and torque by applying the optimum current switching vector.[12] The synchronous reference frame current vector components[19] I_{qs} and I_{ds} used to regulate the torque and flux respectively. Most of the application the I_{ds} has fixed [13],[14] and its normal value and motor torque produces its maximum torque by regulating I_{qs}. DTC – CSI fed drives used for variable speed operation in industry. The main advantages of DTC drive is less parameter utilization such as stator resistance. The stator resistance estimation is very significant to estimate the stator flux and torque[15] [16]. At low speed operation estimation of stator flux deviate from its set value due to variation of stator resistance due to change of frequency and temperature leads the system unstable. To overcome the above draw backs on line stator resistance compensation was introduced by different authors [17]-[20]. To decrease the current harmonics in current source inverters, the filtering capacitor is used on the motor side. The capacitor filter and inductances of motor's form a resonance circuit altogether. The resonance circuit is excited due to sudden change of current generated by the inverter cause lot of oscillation on the motor current and torque ripples which increases the motor harmonic losses. In high-power applications the switching frequency is less due to power switching frequency is less due to power switch delay and high switching losses[4], results in high harmonic components in power source current and voltage waveforms and then the motor suffers from rather high - torque ripple.

The torque produced in the DTC induction motor relies on effectively constructing the stator flux. In DTC[15],[16], the torque and stator flux are regulated to their command values (i_{qs} & i_{ds}) by selecting the switching state which gives the proper changes in the torque and flux. In DTC, the current-vector selection strategy using a switching table is widely used because of its simple concept and easy to be implemented. The proper current vector selection is based on the error in electromagnetic torque, error in stator flux and the position of the stator flux vector. In the conventional

DTC scheme the system makes the relatively large error of torque and/or flux when machine operated at low speed. This was the reason to propose a novel approach of MRAS based torque estimation to overcome above mention drawbacks during low speed and high speed operation. In section II basic concept of CSI Direct Torque Control principle is explained. In section III a novel MRAS based torque estimation for induction motor with direct torque control is introduced. The simulation and experimental results are discussed in section IV.

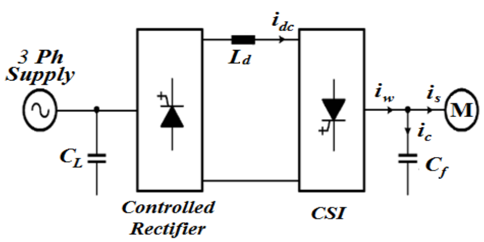


Fig.1 Conventional CSI drive

2. CSI fed drives with Direct torque control system

2.1 DTC of a CSI-fed induction motor

The conventional direct torque controlled induction motor drive fed from current source inverter[11] [12] as shown in Figure 2. It is possible to control directly the modulus of the rotor flux-linkage space vector through the rectifier voltage, and the electromagnetic torque by the supply frequency of the CSI [4].

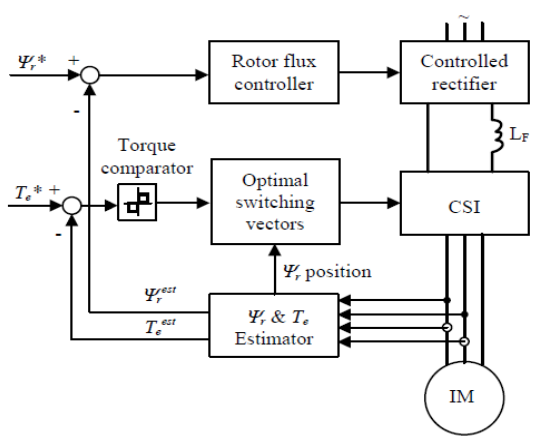


Fig. 2 Basic scheme of DTC CSI-fed IM drive

The inputs to the optimal switching table are the output of a 3-level hysteresis comparator and the position of the rotor flux-linkage space vector. As a result, the optimal switching table determines the optimum current switching vector of current source inverter.

In the classical DTC, there are several drawbacks. Such as sluggish response (slow response) in both start up and changes in either flux or torque. Large and small errors in flux and torque

2.2 Input and Control Variables

The motor input variables are torque Te^* and stator flux amplitude λ_S^*, as in the case of basic DTC. Control variables are current components in synchronous reference frame i_{ds}^* and i_{qs}^* and the phase angle between them (θ_s). D-axis component i_{ds}^* is determined as the output of the PI rotor flux controller, while q-axis component i_{qs}^* is calculated from the input variables and motor parameters:

$$i_{qs}^* = \frac{2L_r}{3pL_m}\frac{1}{\lambda_r^*}T_r \quad ; \quad i_{ds}^* = \frac{1}{L_m}\lambda_r^* \qquad (1)$$

Where L_r is rotor inductance, L_m is mutual inductance and p denotes pair of poles.

Phase angle θ_s and rectifier reference current i_{ref} are obtained as a result of rectangular to polar coordinate transformation:

$$\theta_S = \tan^{-1}\left(\frac{i_{qs}^*}{i_{ds}^*}\right) \qquad (2)$$

$$i_{ref} = \sqrt{(i_{ds}^*)^2 + (i_{qs}^*)^2} \qquad (3)$$

$$\lambda_s^* = \frac{L_m}{L_r}\lambda_r^* + \frac{L_s L_r - L_m^2}{L_r} i_s \qquad (4)$$

2.3 Flux and Torque Estimator

The main feedback signals of DTC are the estimated flux and torque. They are obtained from the outputs of the estimator operating in a synchronous reference frame. This estimator at first performs EMF integration to determine the stator flux vector:

$$\lambda_{ds} = \int (V_{ds} - R_s i_{ds}) dt \qquad (5)$$

$$\lambda_{qs} = \int (V_{qs} - R_s i_{qs}) dt \qquad (6)$$

$$\theta_S = \tan^{-1}\left(\frac{\lambda_{ds}}{\lambda_{qs}}\right) \qquad (7)$$

$$T_e^* = \frac{3}{2} p\left(\lambda_{ds}^* i_{qs}^s - \lambda_{qs}^* i_{ds}^s\right) \qquad (8)$$

and then calculates the flux amplitude and find the sector of 60 degrees in α-β plane where flux vector resides, according to the partition shown in Figure 3.

In that case six intervals of 60 degrees can be defined in which the current and the voltage changes its values. In every interval the current from DC link flows through two inverter legs and two motor phase windings.

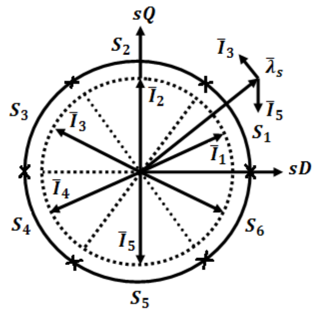


Fig .3 Sectors in $\alpha-\beta$ plane where rotor flux resides

From the stator output current and voltage, pure Integrator in (5) and (6) yields a flux vector.

The trajectory of $\boldsymbol{\lambda_s}$ is exactly circular, it is important to note that the dynamics of stator flux estimation do not depend on the response of the offset estimator. The estimated stator flux is calculated from motor parameters of Stator voltage and current

$$\lambda_s=\sqrt{\left(\lambda_{ds}{}^{s}\right)^2+\left(\lambda_{qs}{}^{s}\right)^2} \tag{9}$$

and its position in α-β reference frame is determined by:

$$\theta_e=\tan^{-1}\left(\frac{\lambda_{qs}{}^{s}}{\lambda_{ds}{}^{s}}\right) \tag{10}$$

Finally, from the estimated stator flux and current vector the motor torque is:

$$T_e=\frac{3}{2}p\left(\lambda_{ds}{}^{s}i_{qs}{}^{s}-\lambda_{qs}{}^{s}i_{ds}{}^{s}\right) \tag{11}$$

Where the stator flux and current vectors are given in synchronous α-β frame and *p* denotes the number of pole pairs.

3. Proposed MRAS based torque and speed estimator

In proposed control system the estimated flux and torque are represented in dq axis component and induction motor is controlled like as a dc motor. The equation of separate controls for torque and flux are [21]:

$$\left|\lambda_s\right|=k_d i_m \Rightarrow \left|\lambda_s\right| \propto i_{mr} \tag{12}$$

$$T_e=k_q i_{sq} \Rightarrow T_e \propto i_{sq} \tag{13}$$

They are obtained as outputs of the estimator in the synchronous reference frame. This estimator at first performs to determine the stator flux vector. The basic relation between torque *Te,* stator flux λ_s and rotor flux λ_r is:

$$T_e=\frac{3}{2}p\frac{L_m}{\sigma L_s L_r}\lambda_s\lambda_r\sin\theta_T \tag{14}$$

where θ_T is the angle between the stator and rotor flux vectors, *p* is pole pair number, L_s and L_r are stator and rotor self inductances, L_m is the magnetizing inductance, and σ is a total leakage factor, $\sigma = 1 - L^2_m/(Ls*Lr)$.

Torque ripple is composed of two terms [21]:

$$\Delta T=-T_e\left(\frac{1}{\tau_s}+\frac{1}{\tau_r}\right)\frac{T_s}{\sigma}+\frac{3}{2}p\frac{L_m}{\sigma L_s L_r}\left[\left(V_s-j\omega_e\lambda_s\right).j\lambda_r\right]Ts \tag{15}$$

Where ω_e is rotor speed and τ_s and τ_r are stator and rotor time constants respectively. Form the equation (15) the first term is proportional to the torque value and is independent of motor voltage is due to stator and rotor resistances and acts in order to reduce the torque value. The second term represents the effect of the stator voltage on the torque varies and depends on the operating conditions [21]. It is obvious from (14) and (15) that the rotor flux has not any effect on torque in the first term, whereas it has a high effect on the second one. The Rotor flux normally estimated in two ways, one is voltage model and the other is the current model. The former is applicable for high speed and latter for low speed. These two fluxes are introduced to estimate the speed for sensorless speed control called Model Referencing Adaptive System (MRAS) [20]. In proposed method the Electromagnetic torque and speed are estimated from stator flux(Reference Model or Voltage model) and rotor flux (Adaptive model or Current model) from the following equation.

From the Voltage model equation

$$\lambda_{dr(v)}=\frac{L_m}{L_r}\left(\lambda_{ds}-\sigma L_s i_{ds}\right)$$

$$\lambda_{qr(v)}=\frac{L_m}{L_r}\left(\lambda_{qs}-\sigma L_s i_{qs}\right) \tag{16}$$

$$\lambda_{r(v)}=\sqrt{\left(\lambda_{dr}\right)^2+\left(\lambda_{qr}\right)^2} \tag{17}$$

$$\lambda_{s(v)}=\frac{L_m}{L_r}\lambda_r(v)+\frac{L_sL_r-L_m{}^2}{L_r}i_s \tag{18}$$

Form Current Model (Adaptive Model)

$$\lambda_{dr(I)}=\int\left(\frac{L_m}{\tau_r}i_{ds}-\omega_r\lambda_{qr}-\frac{1}{\tau_r}\lambda_{dr}\right)$$

$$\lambda_{qr(I)}=\int\left(\frac{L_m}{\tau_r}i_{qs}-\omega_r\lambda_{dr}-\frac{1}{\tau_r}\lambda_{qr}\right) \tag{19}$$

$$\lambda_{r(I)}=\sqrt{\left(\lambda_{dr}\right)^2+\left(\lambda_{qr}\right)^2} \tag{20}$$

$$T_e = \frac{3}{2} p \frac{L_m}{\sigma L_s L_r} \lambda_{s(V)} \lambda_{r(I)} \sin \theta_T \quad (21)$$

$$\omega_e = \left(K_p + \frac{K_I}{s} \right) e_\omega \quad (22)$$

Where

$$e_\omega = \lambda_{dr(I)} \lambda_{qr(v)} - \lambda_{qr(I)} \lambda_{dr(v)}$$

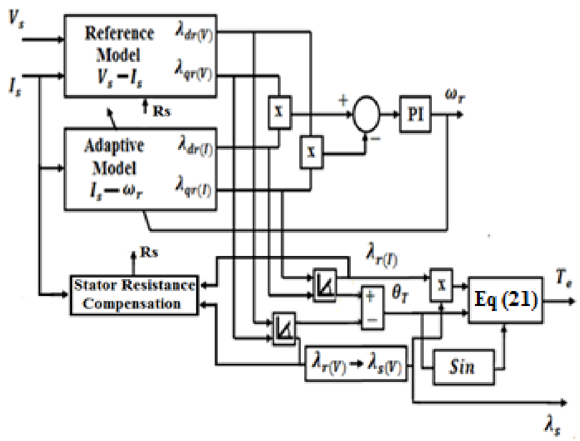


Fig .4 MRAS based Speed and Torque Estimation

The Fig. 4 shows the proposed MRAS based Speed and torque estimation with stator resistance compensation.

In high power electrical drives the semiconductor devices cannot operate at high switching frequency. As a consequence, it is not possible to achieve full control of flux and torque. Since the flux error is not introduced to the switching table in conventional CSI fed induction motor drive[11], the torque error is the only one input in the basic DTC scheme. In proposed system the flux error is introduced to the switching table. The stator resistance variation during low speed operation is the main drawbacks of DTC which leads the system become degrades. The stator resistance compensation [20] introduced in proposed system to estimate the stator flux from voltage model as shown in Fig.4.

The stator flux and Torque calculated from the machine terminal voltage and current. The signal computation block also calculate the sector number S(k) (where k= 1,2,3…6) in which the flux vector λs lies. There are six vectors (each π/3 angle wide)as indicated in figure.3 The over all control system of proposed method is shown in Figure 5. The current vector table block for the proposed MARS based DTC system receive the signals Δλs and ΔTe and S(k) and generates the approximate current control vector (switching states) for the inverter by a lookup table shown in Table.1 applies the selected current vector which essentially affects both torque and flux simultaneously.

For example an operation in sector 2 the Δλs = -1 and ΔTe = +1 the flux is too high and torque is too low generate current I_4. In same sector 2 the Δλs = +1 and ΔTe = +1 and this will generate the I_3vector from the table. The reference current I^*_d generated from flux and torque error through the PI controller and compared with I_d to control the rectifier.

Table 1-Optimum Current Switching-Vector Look-Up Table

Δλs	ΔTe	S1	S2	S3	S4	S5	S6
1	1	I_2	I_3	I_4	I_5	I_6	I_7
	0	I_0	I_0	I_0	I_0	I_0	I_0
	-1	I_6	I_1	i_2	I_3	I_4	I_5
-1	1	I_3	I_4	I_5	I_6	I_1	I_2
	0	I_0	I_0	I_0	I_0	I_0	I_0
	-1	I_5	I_6	I_1	I_2	I_3	I_4

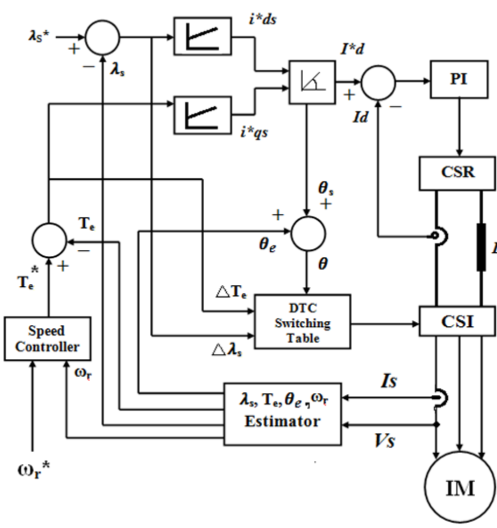


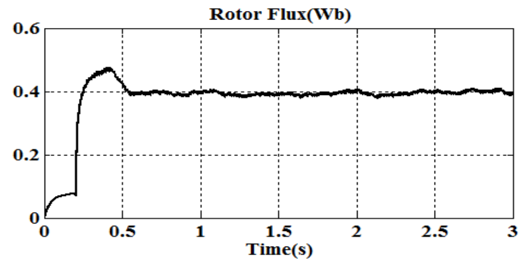
Fig.5 Proposed DTC-SVM Control scheme for CSI fed IM drive

3. Results

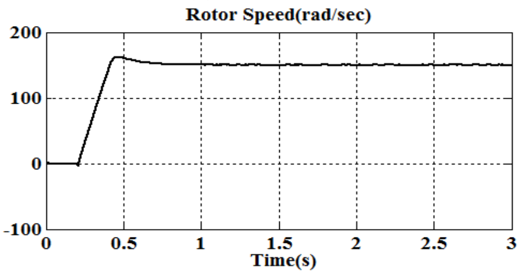
4.1 Simulation Results

A complete drive system of MRAS based DTC with current source inverter fed induction motor has been simulated to study the performance of conventional and proposed method. The system performance is investigated with speed range 150 rad/Sec and 15 rad/Sec with full load for 4 poles, 50 HP motor drives.

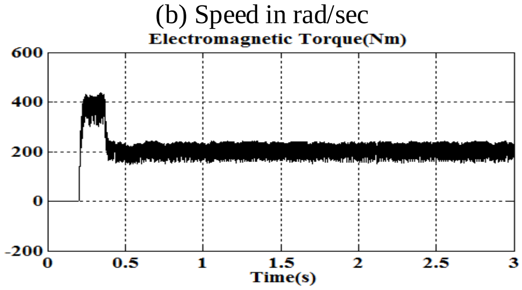
The inverter switching frequency has been set at 2kHz. The comparison results for conventional DTC (Fig 6 and 7) and proposed DTC are shown (Fig. 9 and10) in terms of the rotor flux (λ_r), speed (ω_r) and Torque (T_e).



(a) Rotor Flux



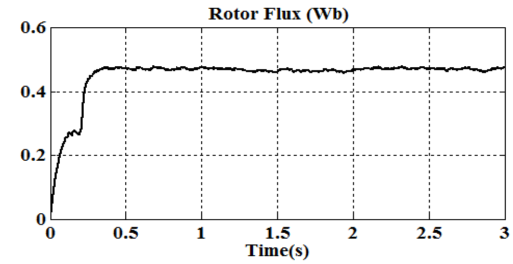
(b) Speed in rad/sec



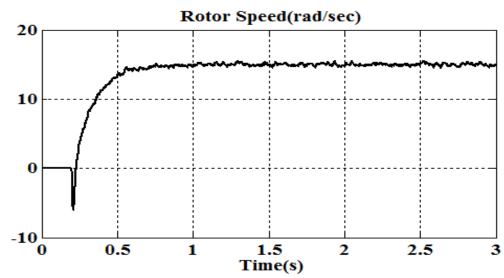
(c) Torque

Fig. 6 Simulation Results for conventional DTC (High Speed)

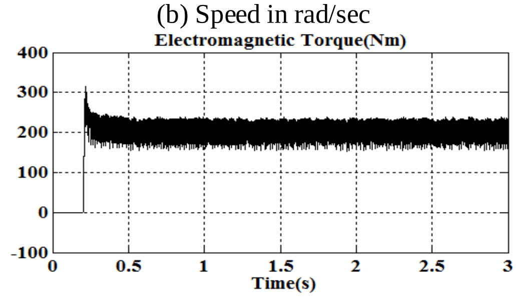
It is seen that the traditional DTC works well at high speed and the rotor flux maintain its set value. The torque is mainly constructed with stator and rotor flux.(Equation 14) At low speed due to variation of stator resistance, the stator flux value deviated from its original value results torque ripples (±30Nm from its normal rated value). Overcome this drawback by proposed MRAS based torque estimation and it shows that the effectiveness of the proposed DTC work well at both high speed and low speed. Fig. 8 & 9 shows that the performance of proposed method of MRAS based torque estimation during high speed and low speed respectively. From Fig 8(a) and 9(a) the rotor flux has been maintained in its set value and torque (Equation-21) having less ripples (±8 of its normal value). The comparision results of torque for conventional and proposed method with Focused Values is shown in Fig. 10(a) & 10(b) respectively. From the above results it is proved that the proposed method is performed well both low and high speed.



(a) Rotor Flux

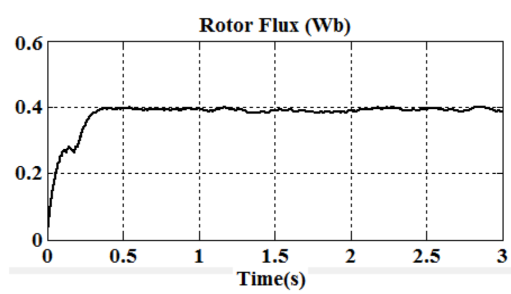


(b) Speed in rad/sec

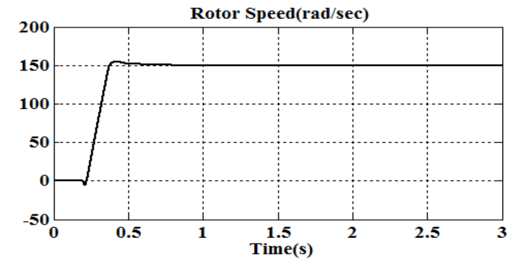


(c) Torque

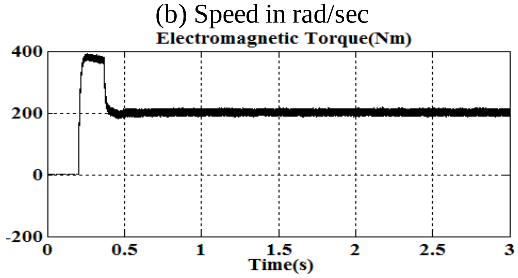
Fig.7 Simulation Results for conventional DTC (Low Speed)



(a) Rotor Flux

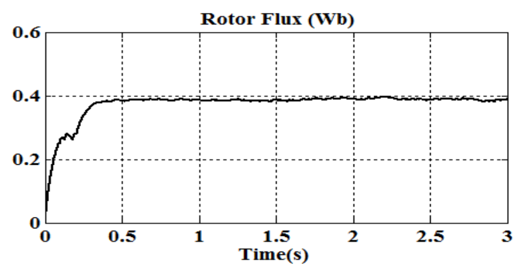


(b) Speed in rad/sec

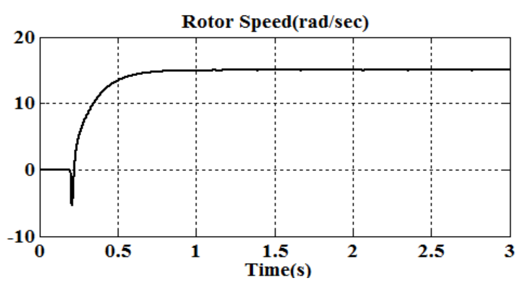


(c) Torque

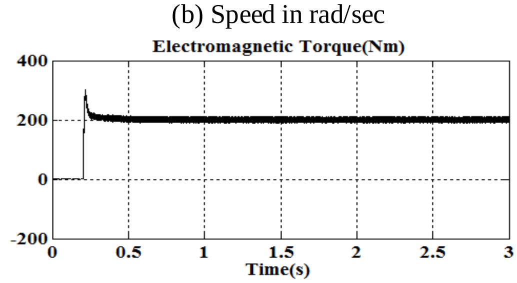
Fig. 8 Simulation Results for proposed control (High Speed)



(a) Rotor Flux

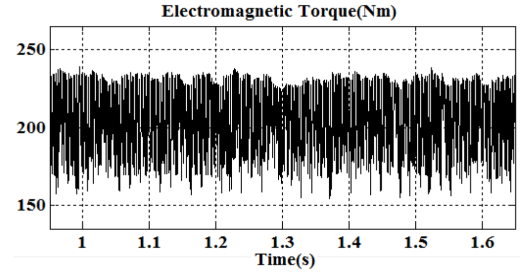


(b) Speed in rad/sec

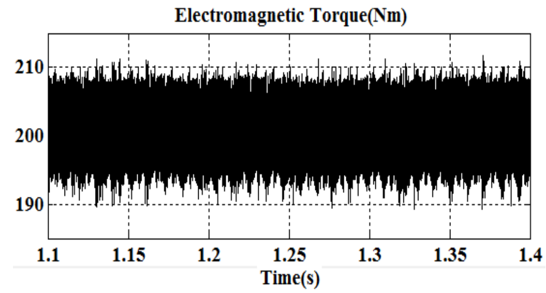


(c) Torque

Fig.9 Simulation Results for proposed DTC with MRAS control (Low Speed)



(a) Conventional method.



(b) Proposed method

Fig 10 Focused Values of Torque

4.2 Experimental results

In order to make the experimental validation of the effectiveness of the proposed method in DTC-CSI fed drive at low speed operation, a DSP-based induction motor drive system has been built. Block diagram for hardware implementation of proposed drive as shown in Fig. 11. The mechanical part of the drive contains the Induction Motor and a loading DC motor.

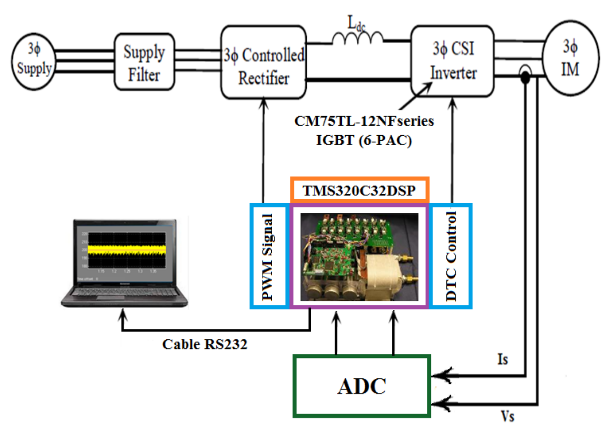
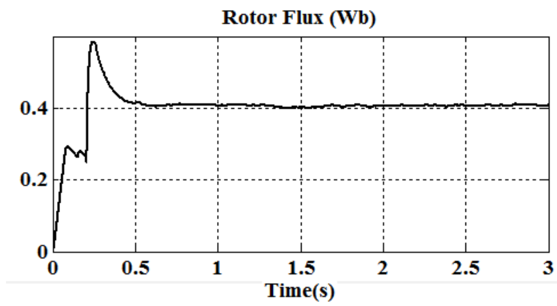
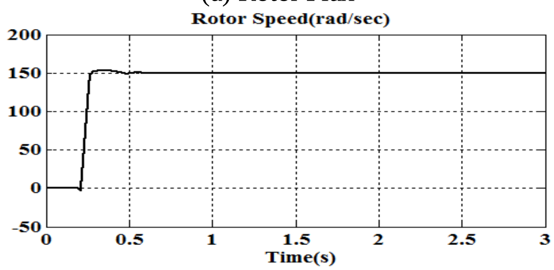


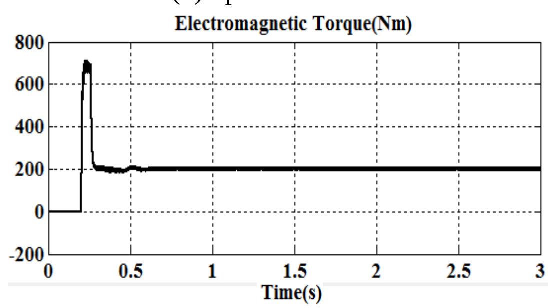
Fig. 11. Block diagram for hardware implementation



(a) Rotor Flux

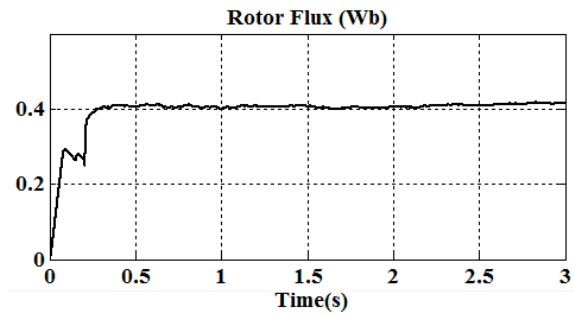


(b) Speed in rad/sec

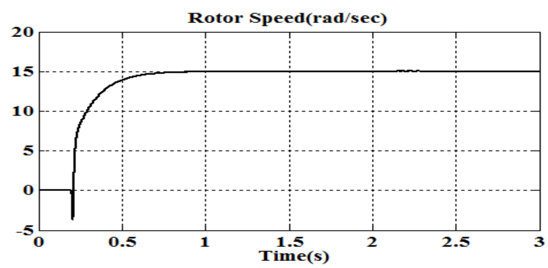


(c) Torque

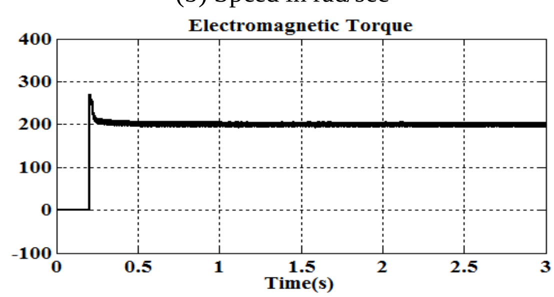
Fig. 12 Experimental Results for proposed scheme (High Speed)



(a) Rotor Flux



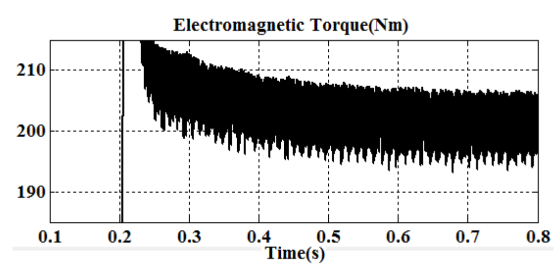
(b) Speed in rad/sec



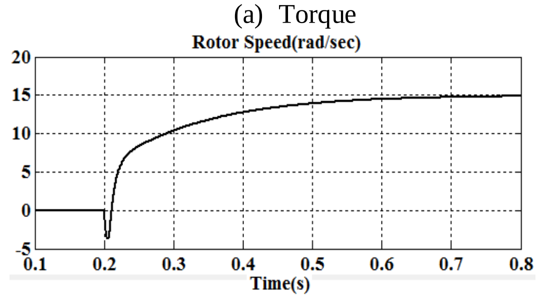
(c)Torque

Fig. 13 Experimental Results for proposed Scheme (Low Speed)

The experimental setup includes a fully digital controlled IGBT inverter with same motor parameter. The control scheme has been implemented on a 20-Mhz fixed point TMS320C32DSP. All measured and controller internal variables are accessible through the serial link to the PC, where graphical data-analysis software can be run. The sampling time is taken as 20 µs. Fig. 12and 13 shows that the experimental results for the rotor flux, speed of 150rad/Sec for high speed and 15rad/Sec for low speed with full load by using in proposed DTC. From Fig 12(a) and 13(b) it shows that the rotor flux has been maintained it set value for both high and low speed. The torque ripple has been reduced (±5N-m from ± 30N-m in conventional method) as shown in Fig.15, when the step response applied to motor at 0.2 sec. The proposed torque control gives better dynamic performance with reduced torque ripples. The zooming results shown in Fig. 14., both the torque and speed reached it seady state at 0.7 sec.



(a) Torque



(b) Speed in rad/sec

Fig. 14 Experimental Results – (Focused Values)

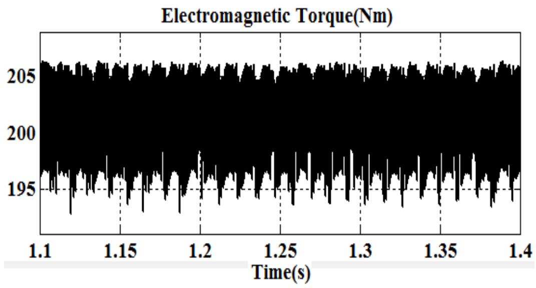


Fig. 15 Experimental Results for proposed Scheme-Focused Values (Low Speed)

Conclusions

A MRAS based torque estimator introduced in this paper to estimate the speed and Torque for the direct torque controlled current source inverter fed induction motor that provides an optimal operating point for the motor. The present method can directly established an effective stator and rotor flux to induce the desired torque by observing the speed error. Simulation and experimental results demonstrate significant reduction in torque ripple as well as increase the dynamic performance of the drive in high-power application using the MRAS estimator.

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