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Rotor Flux – MRAS Based Speed Estimation Technique For Direct Torque Controlled Induction Motor

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Abstract

A rotor flux based Model Reference and Adaptive Scheme (RF-MRAS) space vector pulse width modulated (SV-PWM) direct torque controlled (DTC) induction motor drive, having reduced torque ripple even at low operating speeds and maintaining constant switching frequency has been studied and implemented. In this project a flux estimation scheme is proposed for both reference and adaptive model of MRAS, which improves the performance to a considerable extent. In order to reduce torque ripple, flux ripple and device switching loss, symmetrical switching strategy of space vector pulse width modulation is utilized in this scheme.

I – Introduction

From last decade to become one possible alternative to the well-known Vector Control of Induction machines, Direct torque control (DTC) of induction motor drives offers high performance in terms of simplicity in control and fast electromagnetic torque response With dominant characteristics, direct torque control induction motor as become popular so far its application in industries concerned. A switching look-up table [1] is included for selection of voltage vectors feeding the induction motor. DTC based drives are controlled in the manner of closed loop system without losing current loops in comparison with the vector control drives. However torque response characteristics of both types of drives are same. Due to its simplicity and control algorithm DTC has became popular. Modern high performance drives are expected to operate without sensing speed of the system by means of a speed encoder is undesirable in a drive because it adds cost reliability, shaft extension and mounting arrangement problems. In view of this extensive research has being carried out in the field of sensorless DTC based induction motor drive. However the speed estimation is normally complex and heavily dependent on parameter, particularly near zero speed and imposes a challenge in the accuracy of speed estimation. Several s sensorless speed estimation schemes have been proposed among them Model reference adaptive scheme (MRAS) [3] has become popular because of its simplicity and compensate machine parameters. However in this scheme rotor flux synthesis based on the reference model is difficult to implement particularly at low speeds, because of combination of high pass and low pass during transient state there are some oscillations in torque. In this paper a flux estimation scheme has been proposed, in order to reduce torque oscillations, ripple and device switching losses, symmetrical switching strategy of space vector pursuit modulation [4] [5] is utilized in this scheme. This paper presents the complete sensorless solution based on a DTC-SVM strategy and detailed simulation has been carried out to verify the performance of the scheme.

II. Principles of Operation

Machine Modeling.

The machine model equations in general reference frame are given below,

$$V_s = R_s i_s + p\Psi_s + j\omega_e \Psi_s \quad (1)$$

$$0 = R_r i_r + p\Psi_r + j(\omega_e - \omega_r)\Psi_r \quad (2)$$

$$\Psi_s = L_s i_s + L_m i_r \quad (3)$$

$$\Psi_r = L_r i_r + L_m i_s \quad (4)$$

Where V_s is stator voltage, R_s, R_r are stator and rotor resistances respectively, i_s, i_r are stator and rotor current, Ψ_{ds}, Ψ_{qs} are stator flux linkages, L_s, L_r are stator and rotor self inductances, L_m is the mutual inductance, T_e, T_L are the electromagnetic and load torque, ω_r, ω_e are rotor and reference field speed. For stationery reference frame the machine model equations will be modified to the following equations, where 's' denotes the stationary reference frame

$$V_s^s = R_s i_s^s + p\Psi_s^s \quad (5)$$

$$0 = R_r i_r^s + p\Psi_r^s - j\omega_r \Psi_r^s \quad (6)$$

$$\Psi_s^s = L_s i_s^s + L_m i_r^s \quad (7)$$

$$\Psi_r^s = L_r i_r^s + L_m i_s^s \quad (8)$$

$$T_e = T_L + jp\omega_m \quad (9)$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\Psi_{ds}^s\, i_{qs}^s - \Psi_{qs}^s\, i_{ds}^s) \quad (10)$$

Basic DTC Scheme.

In DTC it is possible to control directly the stator flux and the torque by selecting the appropriate inverter state. For induction motor drive a simple switching table is used, where depending upon the states of change in flux and torque, particular state vector is chosen. The table used for this purpose is shown TABLE 1.

The command stator flux and torque magnitudes are compared with the respective estimated values and the errors are processed through hysteresis-band controllers.[2] The flux loop controller has two levels and torque control loop has three levels of digital output. From the machine terminal voltage and line current, stator flux, torque and state of the voltage vector are estimated and all these information are fed back to the closed loop controller to generate the switching signals.

TABLE 1

Switching Vector Table For Basic DTC

H_Ψ	H_{Te}	S(1)	S(2)	S(3)	S(4)	S(5)	S(6)
1	1	V2	V3	V4	V5	V6	V1
	0	V0	V7	V0	V7	V0	V7
	-1	V6	V1	V2	V3	V4	V5
-1	1	V3	V4	V5	V6	V1	V2
	0	V7	V0	V7	V0	V7	V0
	-1	V5	V6	V1	V2	V3	V4

Because of the presence of this hysteresis loop torque produce by the induction machine becomes very much fluctuating as we can observe it from the simulation results. But the main advantage of this scheme is the simplicity in implementation as it requires no reference frame transformation which was the basic need for FOC drive.

In fig. 1 six active switching vector and two null vector position are shown

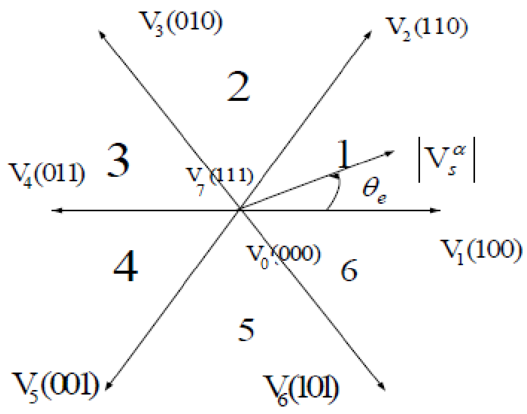

Fig 1: Voltage Vector Positions

The stator flux is estimated as follows:
From eq (5)

$$\Psi_s^s = \int (V_s^s - R_s i_s^s)dt \quad (11)$$

Magnitude of stator flux can be estimated as

$$|\Psi_s^s| = \sqrt{(\Psi_{ds}^2 + \Psi_{qs}^2)} \quad (12)$$

Position of the vector can be estimated as

$$\theta_e = \tan^{-1}(\Psi_{ds}^s / \Psi_{qs}^s) \quad (13)$$

Torque of the machine can be estimated from eq (10). The speed of the machine can be sensed by using a sensor less speed estimation scheme.

Space vector modulation technique (SV-PWM) with symmetrical switching scheme.

Common disadvantages of conventional DTC are high torque ripple and slow transient response to the step changes in torque during start-up. Several techniques have been developed to improve the torque performance. One of them is to reduce the ripples is based on space vector pulse width modulation (SV-PWM or SVM) technique. The main advantage is at each cycle period, a preview technique is used to obtain the voltage space vector required to exactly compensate the flux and torque errors. This leads to better control and fast transient response in machine operation. The basic concept of this scheme is as follows:

If the reference voltage vector is lying in the first sector as shown in the Fig. 1, it can be constructed by its two associate active vector V_1(100), V_2(110) and two null vector V_0(000) or V_7(111) in the same sequence for a specified time. The total time for which the active voltage vectors are applied is called 'effective time'. Power transfer from inverter to motor can take place during this time only. These time intervals can be estimated by comparing volt-second of reference voltage vector with the applied voltage vectors and it can be expressed as

$$T_a = T_z\, a \frac{\sin(\pi/3 - \theta_e)}{\sin(\pi/3)} \qquad (14)$$

$$T_b = T_z\, a \frac{\sin(\theta_e)}{\sin(\pi/3)} \qquad (15)$$

$$T_0 = T_z - (T_a + T_b) \qquad (16)$$

Where $a = \frac{|V_s^s|}{\frac{2}{3} * V_{dc}}$, T_Z is the sampling time, T_a, T_b, T_0 are time intervals for which V_1, V_2 and V_0 or V_7 is applied, θ_e is the angle between the voltage space vectors $|V_s^s|$ and the one of the active vectors(V_1 to V_6) in the direction of rotation the reference vector, and V_{dc} is the DC link voltage of the inverter.

To generate the required inverter control signal, SVM requires only two reference voltage vector(V_{ds}^s, V_{qs}^s) in stator flux oriented reference frame. In this scheme [6] these two vectors are generated by the closed loop controller as shown in fig. 2. The switching pulses are generated depending upon the magnitude and phase angle of the required reference voltage vector as expressed in the following equations:

$$|V_s^s| = \sqrt{(V_{ds}^s)^2 + (V_{qs}^s)^2} \qquad (17)$$

$$\theta_e = \tan^{-1}\left(\frac{V_{qs}^s}{V_{ds}^s}\right) \qquad (18)$$

Timing of the voltage vector applied by the inverter is done by symmetrical switching pattern. If T_z is the total switching time interval, then T_a, T_b will be time intervals during which two active voltage vectors are applied, depending upon the sector in which it is lying. T_0 is the time interval during which the null vector is applied.

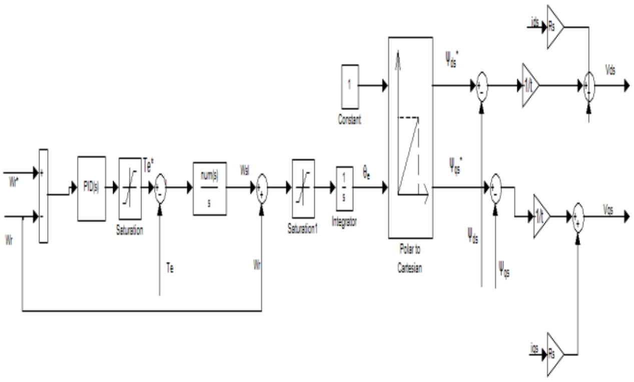

Fig 2 Block diagram of control strategy

Scheme for Flux Estimation.

The sensorless scheme used for speed estimation is rotor flux based MRAS model. The MRAS model is shown in fig 3. By using the combination of high pass filter and low pass filter, while reaching the steady state the torque waveform is having oscillations. So, instead of using combination of high pass and low pass filters, only a low pass filter is used. By using this scheme the oscillations can be reduced. This is the proposed scheme in this paper. In general high pass filter is realised as a PD controller and low pass filter is realised as PI controller. The reference model and adaptive model used for estimating rotor flux in MRAS model are expressed as (19) and (20). The complete schematic control block diagram for this scheme is depicted in fig 4

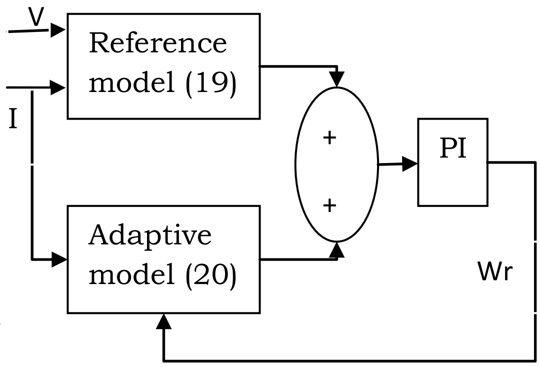

Fig 3 MRAS scheme

$$\frac{d\psi_r}{dt} = \frac{L_r}{L_m} V_s - \frac{L_r}{L_m}(R_s + \sigma L_s s) i_s \qquad (19)$$

$$\frac{d\psi_r}{dt} = \frac{L_m}{T_r} I_s - \omega_r \psi_r - \frac{1}{T_r}\psi_r \qquad (20)$$

$$\sigma = 1 - \frac{L_m^2}{L_r * L_s} \qquad (21)$$

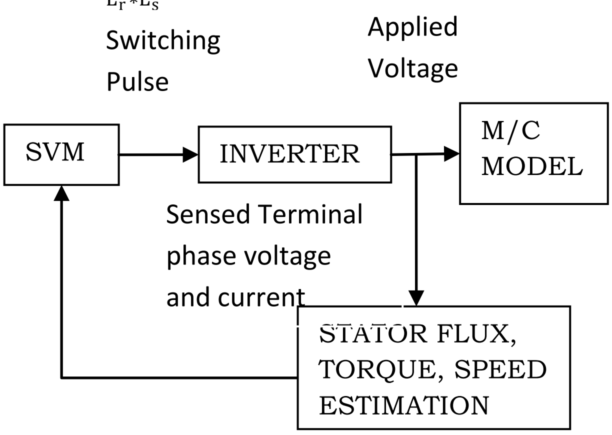

Fig 4 sensorless scheme

Simulation Studies.

Detailed simulation studies are carried out on MATLAB/ simulink platform to verify the operating

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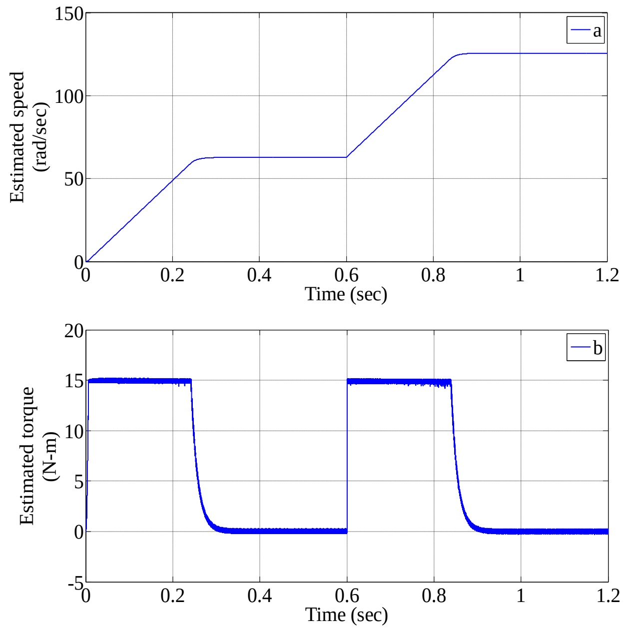
behaviour of the proposed scheme. Machine parameters chosen for carrying out the simulation study are provided in Table 3. Switching frequency of SV-PWM is kept at 10 kHz and simulation step size is kept at 1µsec. performance of the basic DTC scheme is shown fig 5 and 6. Fig. 5(a-c) shows the stator current and torque response due to step change in speed command from 62.8 red/sec to 125.66 red/sec. Performance of the drive due to a step change in load torque command from 0 Nm to 8.0 Nm is depicted in Fig. 6(a-c). It can be observed from this figure that torque ripple is considerable, this is due to the fairly large width of the hysteresis band provided to keep the switching frequency of the switching devices within their rating. Simulated performances of the MRAS with combined high pass and low pass filter scheme utilizing space vector pulse width modulation are depicted in Fig. 7 and Fig. 8. Fig. 7(a-c) shows the stator current and torque response due to step change in speed command from 62.8 red/sec to 125.66 red/sec. The simulated behavior of the system when a step change in load torque from 0 Nm to 8.0 Nm is initiated at 0.8 sec, is shown in Fig. 8 (a-c).

Simulated performances of the MRAS with low pass filter scheme utilizing space vector pulse width modulation are depicted in Fig. 9 and Fig. 10. Fig. 9(a-c) shows the stator current and torque response due to step change in speed command from 62.8 red/sec to 125.66 red/sec. The simulated behavior of the system when a step change in load torque from 0 Nm to 8.0 Nm is initiated at 0.8 sec is shown in Fig. 10 (a-c). Table 2 is the comparison of all the three schemes mentioning the ripple content in each scheme during change in speed and change in load



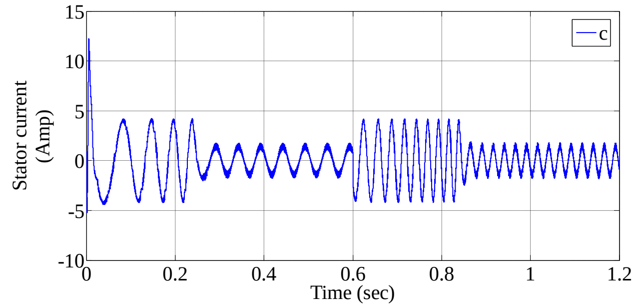


Fig. 5 Simulation results of the basic DTC during change in speed. a) rotor speed b) torque c) motor current

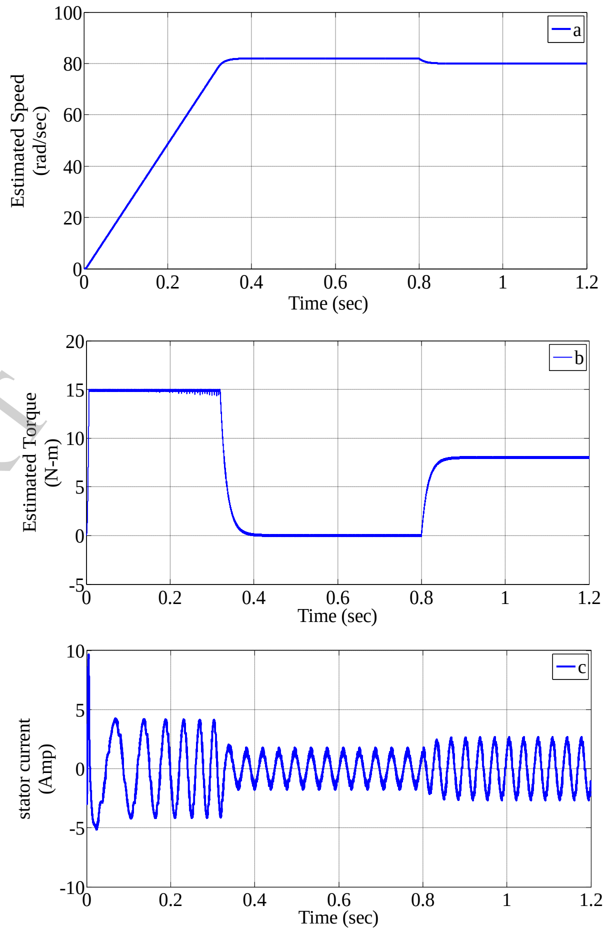
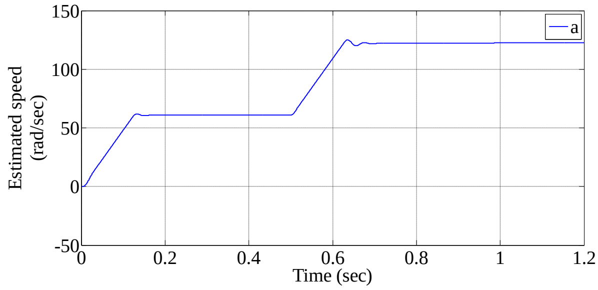


Fig. 6 Simulation results of the basic DTC during change in load torque. a) rotor speed b) torque c) motor current.



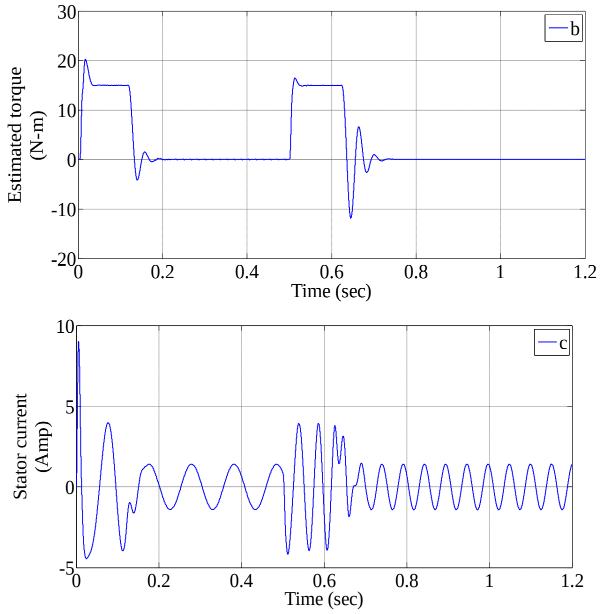


Fig. 7 Simulation results with combined high pass and low pass filter DTC during change in speed. a) rotor speed b) torque c) motor current.

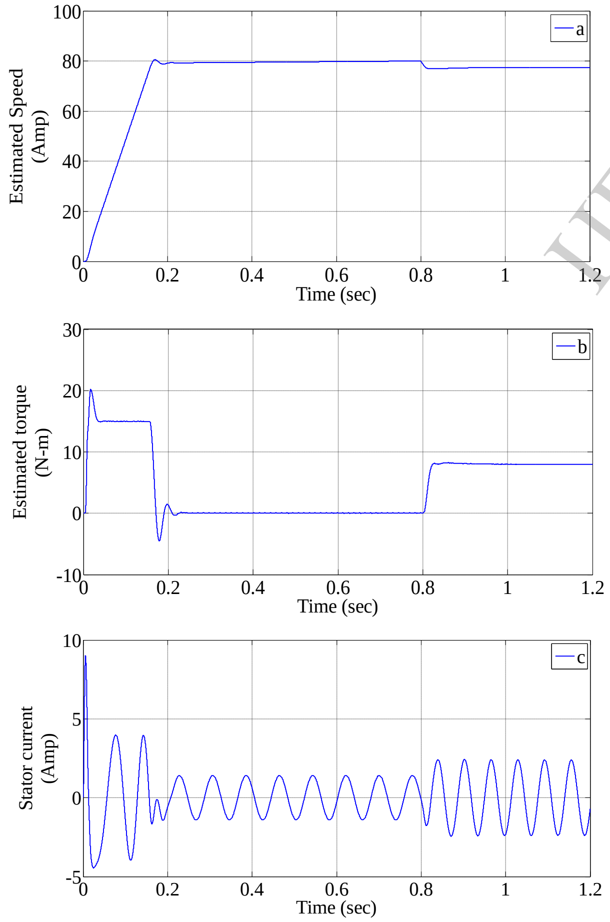


Fig. 8 Simulation results with combined high pass and low pass filter DTC during change in load torque. a) rotor speed b) torque c) motor current.

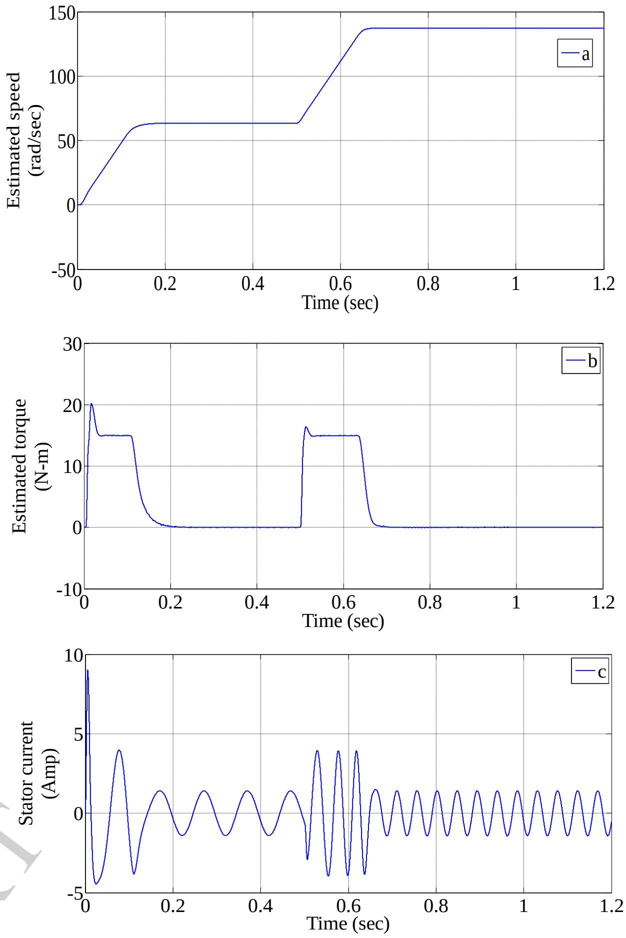
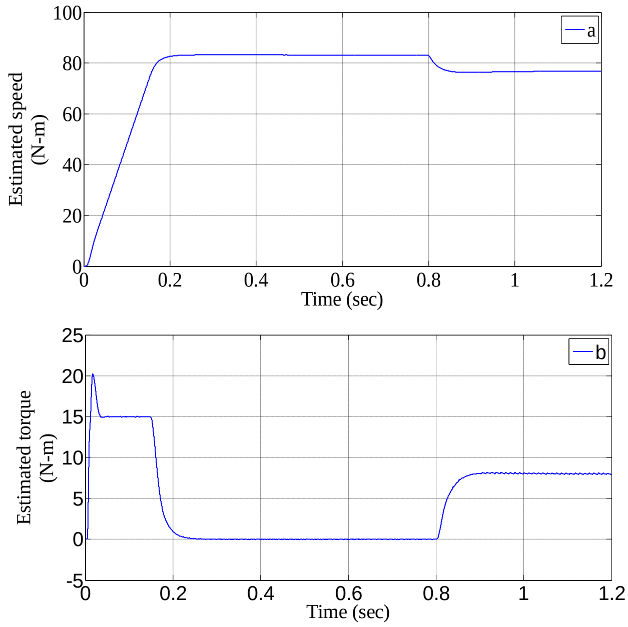


Fig. 9 Simulation results with low pass filter DTC during change in speed. a) rotor speed b) torque c) motor current.



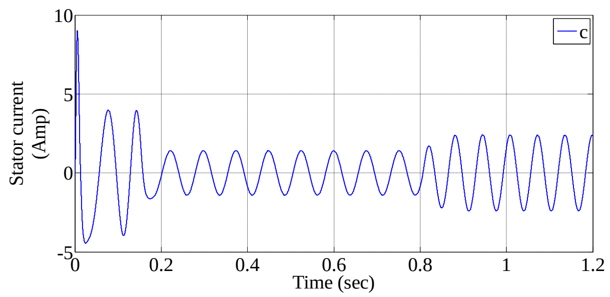


Fig. 10 Simulation results with low pass filter DTC during change in load torque. a) rotor speed b) torque c) motor current.

TABLE 2

Comparison of Schemes

	Basic DTC	MRAS with high pass and low pass filters	MRAS with low pass filter
Torque ripple during change in speed	± 0.2	± 0.02	± 0.015
Torque ripple during change in load torque	± 0.1	± 0.05	± 0.0425
Flux ripple	± 0.02	$\pm 0.475 * 10^{-3}$	$\pm 0.215 * 10^{-3}$

TABLE 3

Machine Parameter Used For Simulation

Induction motor kW rating and No of pole	2.1 kW, 4
Stator and Rotor Resistance (Rs, Rr)	7.83 Ohm, 7.55 Ohm
Stator and Rotor Self Inductance (Lss, Lrr)	21.55 mH, 21.6 mH
Mutual Inductance (Lm)	0.4535 H
Motor Inertia (J)	0.06 kg-m^2

III. CONCLUSION

RF - MRAS based speed estimation technique for Direct Torque Controlled induction motor drive utilizing a low pass filter has been proposed in this paper. The proposed modified scheme demonstrates a good transient and steady state performance, which is confirmed by performing detailed simulation studies

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