ANALYZE THE PERFORMANCE OF CSI FED INDUCTION MOTOR WITH A NOVEL MRAS BASED CONTROLLER TO MINIMIZE THE TORQUE RIPPLE

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Abstract – *A simple mathematical model is constructed to analyze the performance of Sensorless Field oriented controlled Current Source Inverter (FOC - CSI) fed induction motor drive to minimize the torque ripples during low speed operation is proposed in this paper. The estimated torque and stator flux are significant to control the system effectively in FOC. However the torque and stator flux are adversely affected by the stator resistance variations due to temperature and low frequency results torque ripples and the system becomes unstable. A new model reference adaptive system (MRAS) based algorithm for torque estimation is analyzed mathematically in Field oriented vector controlled CSI fed induction motor. The MATLAB/Simulink and hardware results reveal that the proposed method is able to obtain precise flux and torque control, even for very low speed operations.*

Keywords: *Current source inverter, Field oriented control, Induction Motor, MRAS based torque Control.*

1. Introduction

Three phase induction motor is the best choice for industrial drives due to its advantages of simple operation, easy to control, simple construction, reliable and economical. Compare with VSI fed drives CSI fed drive is suitable for medium voltage and high power application [1]-[4] due to simple converter structure, motor-friendly waveforms, inherent four-quadrant operation capability, and reliable short-circuit protection. Vector control allows [5] & [6] high power Current source inverter fed IM drives application to improve the system performance and reliability. Several vector control techniques have been proposed earlier to improve the system performance [7]-[10], power factor improvement [11] and reduce the torque ripple [3]. Vector control can be separated into two categories, direct and indirect control schemes. The CSI fed drive performed well [12] during high speed with different load. In vector control the machine parameter is required to estimate the torque and stator flux particularly stator resistance. The stator resistance value is not dominant in the high speed range in rotor-flux-oriented control method. During low speed operation, the stator resistance value becomes critical for the calculations and produces a significant estimation error results the system become unstable. An accurate value of the stator resistance is crucial importance for correct operation of a sensor less drive in the low speed region. As consequence, numerous on-line schemes for stator resistance estimation have been proposed in past as identification of stator resistance by a ninth-order estimation algorithm (13), an analysis of the effect of the stator resistance variations on the flux estimation is based on estimating the steady-state magnitudes of the stator and rotor flux space phasor using the reactive power is presented in (14). A new technique-the back electromagnetic force (BEMF) detector-for reducing the adverse effects of stator resistance on field-oriented control is presented (15), wherein the stator and rotor resistances are periodically updated by self-tuning operation is achieved in (16). The identification method for stator resistance is derived from the steady-state equations of induction motor dynamics (17), stator resistance identifier using the d-axis flux (18), rotor resistance is estimated in proportion to the estimated stator resistance (19) MRAS based speed estimation without stator resistance (20) with stator resistance (21) are some method implemented in voltage source inverter to improve the performance of the system. In recent online stator resistance identification implemented in CSI fed IM drive in (22).Vector controlled drive with parameter identification algorithm of a MRAS based technique implemented mostly in voltage source inverter during low speed operation. This paper proposed MRAS based technique implemented in CSI fed drives very first time and analyzed by mathematically.

The filter capacitor is connected in output side of CSI inverter to reduce the harmonics and improve the power factor. The capacitor filter and motor inductance of motor's form a resonance circuit altogether. The resonance circuit is excited due to sudden change of current generated by inverter cause lot of oscillation on motor current and torque ripples. In proposed method torque is estimated from MRAS based control. Stator flux estimated from reference model and rotor flux estimated from adjustable model are utilized effectively to estimate the torque.

The mathematical analysis of existing and proposed method for MRAS based technique in sensor less FOC - CSI fed drives is proposed in this paper. Finally the performance results are verified by MATLAB/SIMULINK and hardware in terms of speed, torque step variation during low and high speed.

2. Modeling of 3 Phase Induction Motor Drive

In this section the mathematical model of Induction motor is described. The basic equations of induction motor are the stator voltage equation and rotor voltage equation can be represented in synchronously rotating reference frame (d – q) as follows.

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & \omega_e L_s & pL_m & \omega_e L_m \\ -\omega_e L_s & R_s + pL_s & -\omega_e L_m & pL_m \\ pL_m & (\omega_e - \omega_r)L_m & R_r + pL_r & (\omega_e - \omega_r)L_r \\ -(\omega_e - \omega_r)L_m & pL_m & -(\omega_e - \omega_r)L_r & R_r + pL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \tag{1}$$

Solving the above equation we get

$$\begin{bmatrix} pi_{ds} \\ pi_{qr} \\ pi_{dr} \\ pi_{qr} \end{bmatrix} = \frac{1}{L_c} \begin{bmatrix} -R_s L_r & \omega_c L_c + \omega_r L_m^2 & R_r L_m & \omega_r L_m L_r \\ -(\omega_c L_c + \omega_r L_m^2) & -R_s L_r & -\omega_r L_m L_r & R_r L_m \\ R_s L_m & -\omega_r L_m L_s & -R_r L_s & \omega_c L_c - \omega_r L_s L_r \\ \omega_r L_m L_s & R_s L_m & -(\omega_c L_c - \omega_r L_s L_r) & -R_r L_s \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix}$$

$$+ \frac{1}{L_c} \begin{bmatrix} L_r & 0 & 0 & 0 \\ 0 & L_r & 0 & 0 \\ -L_m & 0 & 0 & 0 \\ 0 & -L_m & 0 & 0 \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \\ 0 \\ 0 \end{bmatrix} \tag{2}$$

Where $L_c = L_s L_r - L_m^2$; and $p = \frac{d}{dt}$

Form the above equations the stator and rotor flux linkage can be determined as follows:

$$p\lambda_{dqs} = v_{dqs} - R_s i_{dqs} - \omega_e \lambda_{qds} \tag{3}$$

$$p\lambda_{dqr} = v_{dqr} - R_r i_{dqr} - (\omega_e - \omega_r)\lambda_{qdr} \tag{4}$$

The electromagnetic torque equation of induction motor as

$$T_e = \frac{3}{2} P\left(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}\right) \tag{5}$$

3. Conventional FOC-CSI fed drive System and its Control Scheme

The block diagram of a current source drive system with FOC control scheme shown in Fig.1. The current source drive consists of an input LC filter, a PWM CSR, a PWM CSI, dc link choke, and an output filter capacitor. A high power induction motor is connected at the output of the drive. A single-bridge configuration is usually used for both the rectifier and the inverter, with which the drive system can be used for medium voltage applications. The drive's input and output filter capacitors are required to assist the commutation of switching devices, while they can also attenuate unwanted harmonics and improve the power factor. The dc choke between the CSR and CSI is used to smoothing the dc current. It also prevents the dc current from sudden increase in case of short-circuit fault and thus provides sufficient time for the protection circuit to function. The FOC scheme for the current source drive system is based on the rotor flux orientation and the decoupled control of the motor flux and torque provides improved dynamics and stability. For the rotor flux estimation, voltage model rotor flux identification method (reference model) combined with current model method (Adjustable model) is implemented for an optimal system performance. The current model method can estimate the rotor flux precisely at low rotor speeds with the stator frequency of a few Hertz.

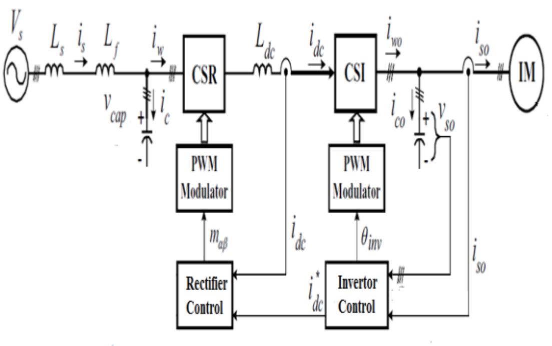


Fig.1 Field oriented control Current source inverter drive system

4. Performance analysis of MRAS based Speed Estimator

Mathematical analysis of MRAS based speed estimator described in this section and block diagram is illustrated in Fig. 2, where the two left-hand side blocks perform integration of equations (6) and (7). The reference (voltage) model and adjustable (current) models are derived by the stator voltage and currents. The estimator operates in the synchronously reference frame and it is described with the following equations:

$$p\lambda_{rv} = \frac{L_m}{L_r}[v_s - (R_s + \sigma L_s p)i_s] \quad (6)$$

$$p\lambda_{rI} = \frac{L_m}{T_r} i_s - \left(\frac{1}{T_r} - j\omega\right)\lambda_{rI} \quad (7)$$

$$\omega_r = \left(K_{p\omega} + \frac{K_{I\omega}}{p}\right) e\omega_r \quad (8)$$

$$e\omega_r = \lambda_{rI} \times \lambda_{rv} = \lambda_{\alpha rI}\lambda_{\beta rv} - \lambda_{\beta rI}\lambda_{\alpha rv} \quad (9)$$

Symbol '*p*' stands for *d*/*dt*, T_r is the rotor time constant and $\sigma = 1 - \frac{L_m^2}{L_s L_r}$. All the parameters in the motor and the estimator are assumed to be of the same value, except for the stator resistance. All variables are space vectors, and sub-scripts *v* and *I* stand for the outputs of the voltage (reference) and current (adjustable) models, respectively. Voltage, current and flux are denoted with *v*, *i* and λ respectively, and subscripts *s* and *r* stand for stator and rotor, respectively. Superscript *s* in space vector symbols denotes the synchronously reference frame.

As is evident from (6)-(9) and Fig. 2, the adaptive mechanism (PI controller) relies on an error quantity that represents the difference between the instantaneous positions of the two rotor flux estimates. The main drawbacks of this method is when operated at low speed due to stator

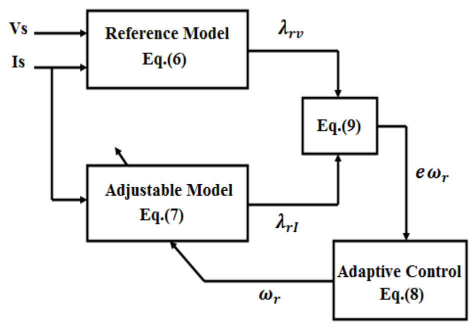


Fig 2 Basic configuration of MRAS based speed estimator without stator resistance compensation

resistance variation the rotor flux estimation from reference model make a error results system become unstable. Hence it is necessary to compensate the stator resistance. The second degree of freedom, the difference in amplitudes of the two rotor flux estimates, is utilized to estimate rotor speed and stator resistance. The mathematical analysis of MRAS estimation with stator resistance compensation method is developed in the next section will make use of this second degree of freedom to achieve simultaneous estimation of the two quantities such as speed and stator resistance. The role of the reference and the adjustable model will be interchanged for this purpose, since the rotor flux estimate of (7) is independent of stator resistance.

5. Performance Analysis of a MRAS based Stator Resistance and Speed Estimator

Parallel rotor speed and stator resistance estimation scheme is designed based on the concept of hyper stability [21] in order to make the system asymptotically stable. For the purpose of deriving an adaptation mechanism it is valid to initially treat rotor speed as a constant parameter, since it changes slowly compared to the change in rotor flux. The stator resistance of the motor varies with temperature, but variations are slow so that it can be treated as a constant parameter, too.

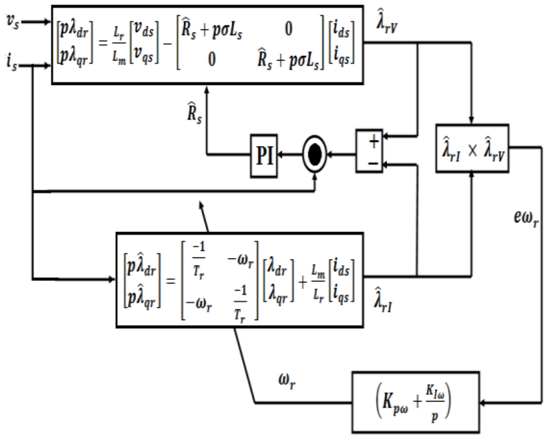


Fig 3 Modeling of the proposed MRAS system with stator resistance compensation

The configuration of the proposed parallel rotor speed and stator resistance is shown in Fig. 3 and is discussed in detail next.

Let R_S and $\boldsymbol{\omega}_r$ denote the true values of the stator resistance in the motor and rotor speed, respectively. These are in general different from the estimated values. Consequently, a mismatch between the estimated and true rotor flux space vectors appears as well. The error equations for the voltage and the current model outputs can then be written as

$$p\lambda_{rv} = \frac{L_m}{L_r}\left[v_s - \left(\hat{R}_s + \sigma L_s p\right) i_s\right]$$

$$p\lambda_{rI} = \frac{L_m}{T_r} i_s - \left(\frac{1}{T_r} - j\omega\right)\lambda_{rI}$$

$$p\varepsilon_v = -\frac{L_r}{L_m}\left(R_s - \hat{R}_s\right) i_s \qquad (10a)$$

$$\varepsilon_v = \lambda_{rv} - \hat{\lambda}_{rv} = \varepsilon_{\alpha V} + j\varepsilon_{\beta V}$$

$$p\varepsilon_I = \left(j\omega - \frac{1}{T_r}\right)\varepsilon_I + j(\omega - \hat{\omega})\hat{\lambda}_{rI} \qquad (10b)$$

$$\varepsilon_I = \lambda_{rI} - \hat{\lambda}_{rI} = \varepsilon_{\alpha I} + j\varepsilon_{\beta I}$$

Symbols λ_{rv} & λ_{rI} stand for true values of the two rotors flux space vectors. Equations (10a)-(10b) can be rewritten in matrix notation as

$$p\begin{bmatrix}\varepsilon_{\alpha I}\\ \varepsilon_{\beta I}\\ \varepsilon_{\alpha V}\\ \varepsilon_{\beta V}\end{bmatrix} = \begin{bmatrix}-\frac{1}{T_r} & -\omega & 0 & 0\\ \omega & -\frac{1}{T_r} & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix} . \begin{bmatrix}\varepsilon_{\alpha I}\\ \varepsilon_{\beta I}\\ \varepsilon_{\alpha V}\\ \varepsilon_{\beta V}\end{bmatrix} - W =$$
$$A\varepsilon - W \qquad (11)$$

Where W is the nonlinear block, defined as follows:

$$W = \begin{bmatrix} -\Delta\omega\begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix} & \begin{matrix}0 & 0\\ 0 & 0\end{matrix}\\ \begin{matrix}0 & 0\\ 0 & 0\end{matrix} & \frac{L_r}{L_m}\Delta R_s\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}\end{bmatrix}\begin{bmatrix}\hat{\lambda}_{\alpha rI}\\ \hat{\lambda}_{\beta rI}\\ i_{\alpha s}\\ i_{\beta s}\end{bmatrix} (12)$$

$$W = \begin{bmatrix}-\Delta\omega J & 0\\ 0 & \frac{L_r}{L_m}\Delta R_S I\end{bmatrix} . \begin{bmatrix}\lambda_{rI}\\ i_s\end{bmatrix}$$

Here $\Delta\omega = \omega - \hat{\omega}$,

$\Delta R = R_s - \hat{R}_s \quad \hat{\lambda}_{rI} = \left[\hat{\lambda}_{\alpha rI} \quad \hat{\lambda}_{\beta rI}\right]^T$,

$i_s = [i_{\alpha s} \quad i_{\beta s}]^T, \quad J = \begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix}$

and $\mathrm{I} = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$

The system is hyper stable if the input and output of the nonlinear block W satisfy Popov's criterion [20]:

$$S = \int_0^{t_1} \varepsilon^T . W dt \geq \gamma^2 . \forall t_1 \qquad (13)$$

Where, using (8)

$$\varepsilon^T . W = -\Delta\omega\left(\varepsilon_I^T . J . \hat{\lambda}_{rI}\right) + \frac{L_r}{L_m}\Delta R_S\left(\varepsilon_v^T . i_s\right) \quad (14)$$

Substitution of (10) into (9) yields

$$S = \int_0^{t_1} \varepsilon^T . W dt$$

$$= \underbrace{-\int_0^{t_1} \Delta\omega\left(\varepsilon_I^T . J . \hat{\lambda}_{rI}\right) dt}_{S_1} + \underbrace{\frac{L_r}{L_m}\int_0^{t_1} \Delta R_S\left(\varepsilon_V^T . i_s\right) dt}_{S_2}$$

$$S = S_1 + \frac{L_r}{L_m} . S_2 \geq -\gamma^2 . \forall t_1 \qquad (15)$$

The validity of (15) can be verified by means of inequalities (16) and (17) with adaptive mechanisms given in (16), (17) for rotor speed estimation and stator resistance identification, respectively:

$$S_1 = -\int_0^{t_1} \Delta\omega\left(\varepsilon_I^T . J . \hat{\lambda}_{rI}\right) dt \geq -\gamma_1^2 \qquad (16)$$

$$S_2 = \int_0^{t_1} \Delta R_S\left(\varepsilon_V^T . i_s\right) dt \geq -\gamma_2^2 \qquad (17)$$

$$\hat{\omega} = \left(K_{p\omega} + \frac{K_{I\omega}}{p}\right)\left(\varepsilon_I^T . J . \hat{\lambda}_{rI}\right) = \left(K_{p\omega} + \frac{K_{I\omega}}{p}\right) e\omega_r \quad (18)$$

$$\hat{R}_s = \left(K_{pR_s} + \frac{K_{IR_s}}{p}\right)(\varepsilon_V^T . i_s) = \left(K_{pR_s} + \frac{K_{IR_s}}{p}\right) e_{R_s} \quad (19)$$

Where $K_{p\omega}$, $K_{I\omega}$, K_{pR_s}, K_{IR_s}, are PI controller parameters of rotor speed and stator resistance adaptation mechanisms, respectively. The value of $\varepsilon_I^T . \boldsymbol{J} . \hat{\lambda}_{rI}$ in (16) is evaluated by taking into account that, for speed estimation, the output of the reference model is taken as equal to the true rotor flux space vector. Hence

$$\underline{\varepsilon}_{\mathrm{I}} = \lambda_{rI} - \hat{\lambda}_{rI} = \hat{\lambda}_{rv} - \hat{\lambda}_{rI} \ ,$$

Since $\lambda_{rI} \equiv \hat{\lambda}_{rv}$,

Thus

$$\underline{\varepsilon}_I^T . J . \hat{\lambda}_{rI}^s = \left[\hat{\lambda}_{\alpha rV} - \hat{\lambda}_{\alpha rI} \quad \hat{\lambda}_{\beta rI} - \hat{\lambda}_{\beta rV}\right] . \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} . \begin{bmatrix} \hat{\lambda}_{\alpha rI} \\ \hat{\lambda}_{\beta rI} \end{bmatrix}$$

$$= \left[\hat{\lambda}_{\alpha rV} - \hat{\lambda}_{\alpha rI} \quad \hat{\lambda}_{\beta rI} - \hat{\lambda}_{\beta rV}\right] . \begin{bmatrix} \hat{\lambda}_{\beta rI} \\ \hat{\lambda}_{\alpha rI} \end{bmatrix}$$

$$= \hat{\lambda}_{rI} \, X \, \hat{\lambda}_{rV} = e_\omega(t) \quad (20)$$

The error quantity for speed estimation is therefore the one of (8). The value of $\underline{\boldsymbol{\varepsilon}}_V^T . \boldsymbol{i}_s^s$ in (17) needs to be evaluated next. In order to do this, it is necessary to take into account that, for stator resistance estimation, reference and adjustable model (6), (7) change the roles. The true value of the rotor flux space vector is now taken to be the output of (7).

Hence

$\varepsilon_{\mathrm{V}} = \lambda_{rv} - \hat{\lambda}_{rv} = \hat{\lambda}_{rI} - \hat{\lambda}_{rv}$, since $\lambda_{rv} \equiv \hat{\lambda}_{rI}$.

One further has

$$-\varepsilon_V^T . i_s = \left[\hat{\lambda}_{\alpha rV} - \hat{\lambda}_{\alpha rI} \quad \hat{\lambda}_{\beta rV} - \hat{\lambda}_{\beta rI}\right] . \begin{bmatrix} \hat{\lambda}_{\alpha rI} \\ \hat{\lambda}_{\beta rI} \end{bmatrix}$$

$$= i_{\alpha s}\left(\hat{\lambda}_{\alpha rV} - \hat{\lambda}_{\alpha rI}\right) + i_{\beta s}\left(\hat{\lambda}_{\beta rV} - \hat{\lambda}_{\beta rI}\right)$$

$$= i_s(\lambda_{rV} - \lambda_{rI}) = e_{R_s}(t) \quad (21)$$

The error quantity for stator resistance estimation is therefore

$$e_{R_s} = i_{\alpha s}\left(\hat{\lambda}_{\alpha rV} - \hat{\lambda}_{\alpha rI}\right) + i_{\beta s}\left(\hat{\lambda}_{\beta rV} - \hat{\lambda}_{\beta rI}\right) \quad (22)$$

It follows from these considerations that the role of the reference and the adjustable models is interchangeable in the parallel system of rotor speed and stator resistance estimation. The speed and stator resistance can be estimated in parallel using (18), (19) at any speed. The rotor speed adaptation mechanism (18) is the same as in the customary MRAS speed estimator reviewed in Section II.

6. Performance Analysis of Proposed MRAS Based Torque Estimation

Field oriented control system the estimated torque and flux 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:

$$|\lambda_s| = k_d i_m \Rightarrow |\lambda_s| \propto i_{mr} \quad (23)$$

$$T_e = k_q i_{sq} \Rightarrow T_e \propto i_{sq} \quad (24)$$

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:

$$T_e = \frac{3}{2} p \frac{L_m}{\sigma L_s L_r} \lambda_s \lambda_r \sin\theta_T \quad (25)$$

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, $\sigma = 1 - L_m^2 /(Ls*Lr)$.Torque ripple is composed of two terms as

$$\Delta T = -T_e\left(\frac{1}{\tau_s} + \frac{1}{\tau_r}\right)\frac{T_s}{\sigma} + \frac{3}{2} p \frac{L_m}{\sigma L_s L_r}\left[(V_s - j\omega_e\lambda_s) . j\lambda_r\right] Ts \quad (26)$$

Where ω_e is rotor speed and τ_s and τ_r are stator and rotor time constants respectively.

Form the equation (26) 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. It is obvious from (25) and (26) 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). 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. The rotor flux can be estimated from the Voltage model equation (Reference Model) as

$$p\lambda_{rv} = \frac{L_m}{L_r}\left[v_s - \left(\hat{R}_s + \sigma L_s p\right) i_s\right] \tag{27}$$

and the stator flux as

$$\lambda_{sv} = \frac{L_m}{L_r}\lambda_{rv} + \frac{L_s L_r - L_m^2}{L_r} \tag{28}$$

Form Current Model (Adaptive Model)

$$p\lambda_{rI} = \frac{L_m}{T_r} i_s - \left(\frac{1}{T_r} - j\omega\right)\lambda_{rI} \tag{29}$$

Hence the torque can be estimated by using the equation (25) as

$$T_e = \frac{3}{2} p \frac{L_m}{\sigma L_s L_r} \lambda_{sv}\lambda_{rI} \sin\theta_T \tag{30}$$

And

$$T_e = T_L + (Jp + B)\omega_r \tag{31}$$

From the above rotor speed can be calculated by

$$\omega_r = \int\left(\frac{P}{2J}\left(T_e - T_L - B\omega_r\right)\right) \tag{32}$$

Where
P = number of poles
J=Moment of inertia
B=Friction co efficient
Simulink model for proposed MRAS based torque estimation control is shown in Fig.4.

Block diagram for whole control scheme for the FOC - CSI fed induction motor, utilized in this paper is illustrated in Fig. 5. It includes, apart from a speed controller, rotor flux and torque controllers as well. The required feedback quantities for the torque and rotor flux closed loop control are obtained from the reference model.

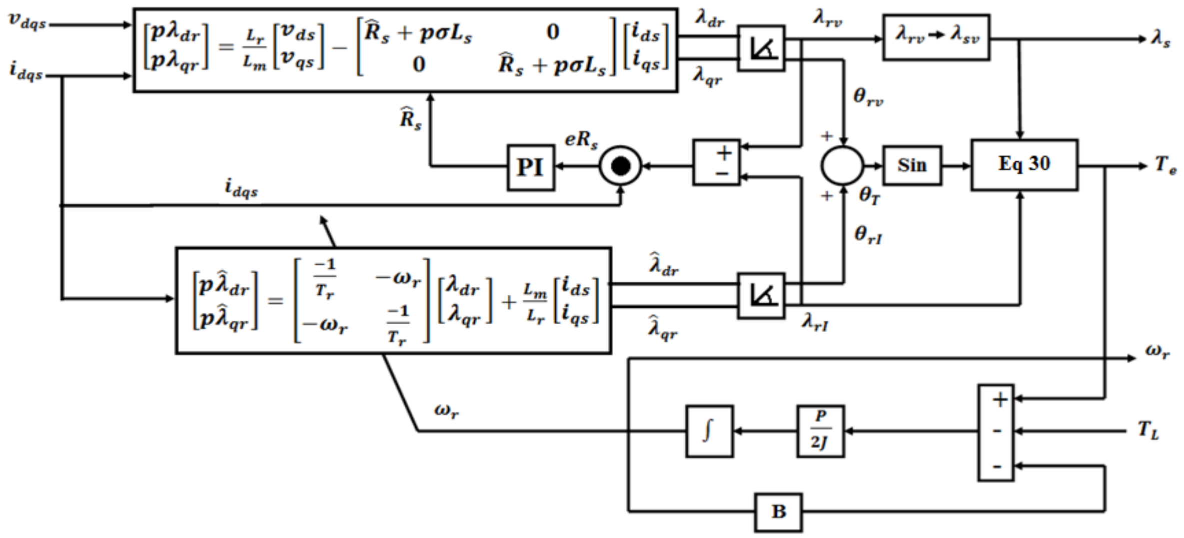


Fig.4 Simulink Model for proposed MRAS based Torque control

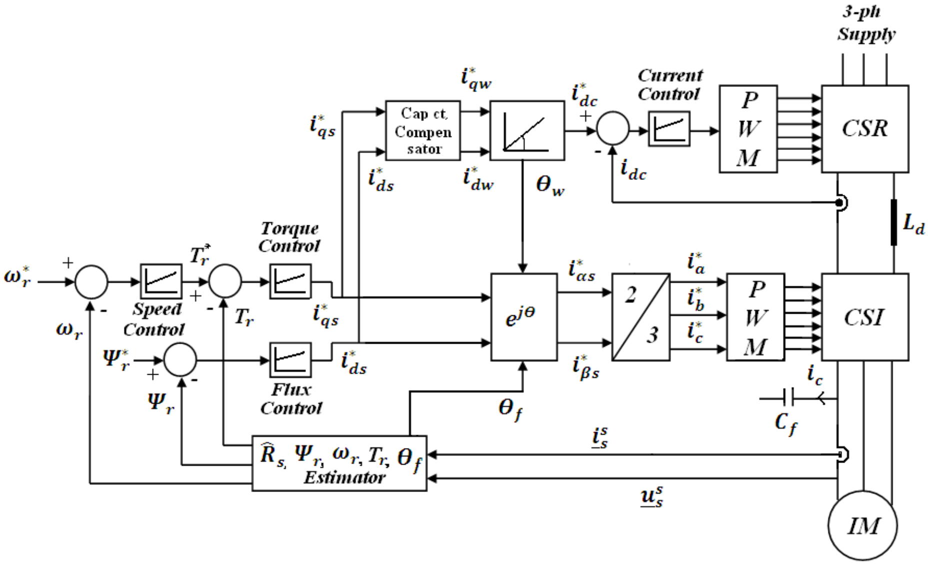


Fig. 5 Proposed control scheme for CSI fed rotor flux oriented induction motor drive

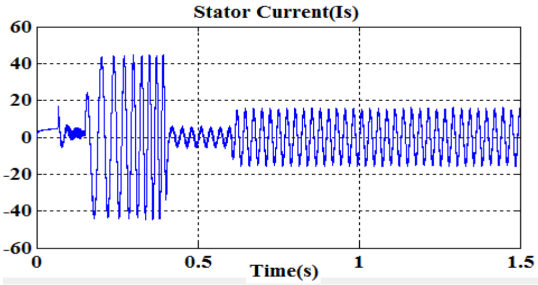
The flux and speed controllers are utilized to generate the motor *d*-axis current (i_{ds}^*) and *q*-axis current (i_{qs}^*), respectively. The sum of stator *d*, *q*-axis currents and the compensated capacitor currents is used to produce the inverter reference *d*, *q*-axis currents (i_{dw}^* and i_{qw}^*). In order to minimize the dc-link current, the amplitude (i_{dc}^*) of the synthesized inverter reference current is served as the reference for dc-link current control of the current source rectifier, while the corresponding phase θ_w is added to the rotor flux angle θ_f for the modulation of the CSI. The current model is utilized for the flux estimation

7. Results

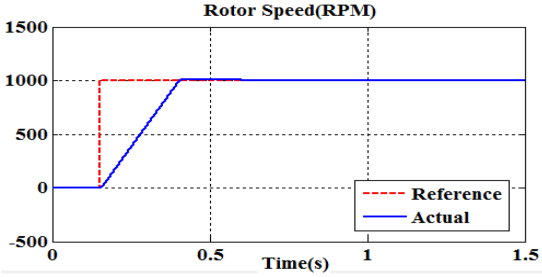
The performance of FOC CSI fed IM drive with conventional MRAS, MRAS with stator resistance compensation and proposed method of MRAS based torque estimation are verified using MATLAB/Simulink software package. The motor parameters are mentioned in Appendix. The experimental results are presented in this section in detail for clear understanding.

7.1 Simulation Results

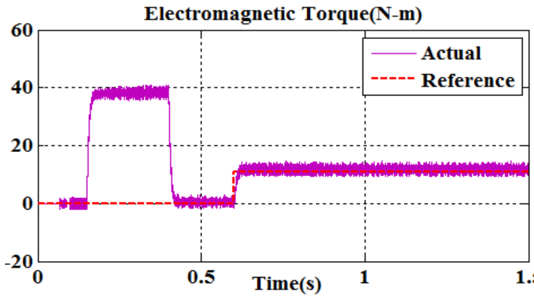
The MATLAB/Simulink software is used to analyze the performance FOC-CSI fed IM drives for constant speed, variable speed and low speed operation respectively. Fig (6) shows that the performance of constant speed operation for conventional MRAS based speed estimator without stator resistance compensation. The motor started at 0.15 sec and reached to its rated speed 1000 rpm at 0.4 sec. The full load was applied at 0.6 sec. Fig (7) shows that variable speed operation the speed vary from 0 to 1000 rpm and to decreased to 100 rpm at 1.5 sec. Here the full load was applied at 2 sec during low speed. Fig (8) shows that the performance of MRAS based speed estimation with zero speed operation with full load. From the results shows that the drive operated well at high speed and poor at low speed due to variation stator resistance and having high ripples in torque as shown in fig (8b). Consequently, the simultaneous estimation of speed and stator resistance was implemented in MRAS based technique. The performance of MRAS with stator resistance control are shown in Fig (9)-(11) analyzed in same way as MRAS based speed estimation. In this method the starting torque is somewhat improved and overshoot in speed before reaching at steady state. The results shows that the performance of MRAS with stator resistance the dynamic performance well at low speed and high speed. But both methods the torque having high ripples (Shows Fig. 8b and Fig. 11b) and speed drops to 8 rpm to reach its steady state at 3 sec for MRAS method and speed drops to 12 rpm to reach its steady state at 1.5 sec for MRAS with stator resistance control. The proposed method the torque is estimated from MRAS based control and speed estimated with feed forward control. Fig (12)-(14) shows that the performance of proposed method analyzed same way for constant speed, low speed and variable speed operation respectively. In this method the torque was estimated from the stator and rotor flux obtained from MRAS controller and the results prove that the system performed well during low speed and high speed operation with full load and speed droop has been reduced



(a)

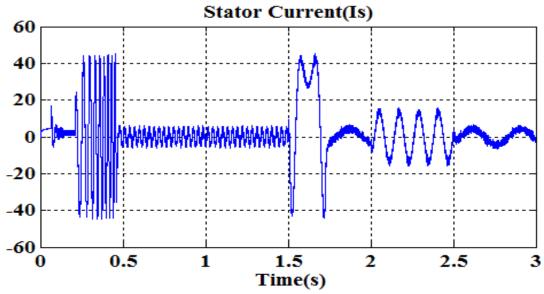


(b)

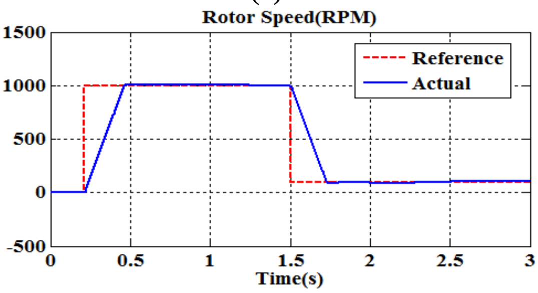


(c)

Fig.(6) Simulation Results – Constant Speed MRAS control without stator resistance compensation a) Stator Current b) Rotor Speed (0-1000rpm) c) Torque



(a)



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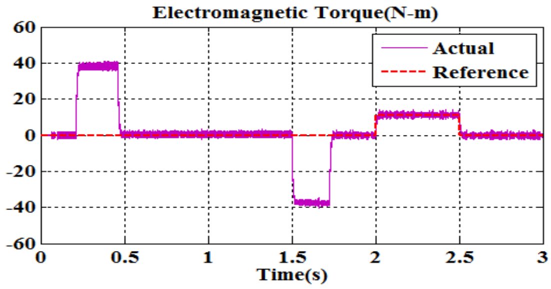


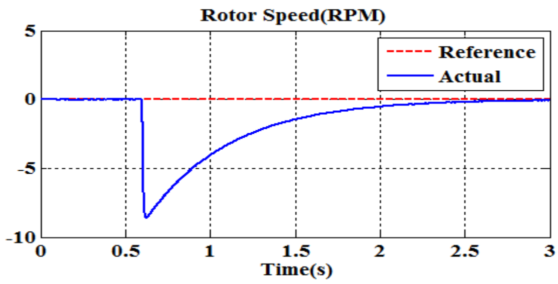
(c)

Fig.(7) Simulation Results – Variable Speed MRAS Control without stator resistance compensation a) Stator Current b) Rotor Speed (0-1000 – 0 rpm) c) Torque

to 4 rpm and reach at steady state at 1.5 sec. also the ripples are reduced significantly during low and high speed operation

7.2 Experimental Results:

An experimental set up for proposed method of FOC – CSI fed induction motor drive using TMS320F2812 DSP based as shown in Fig. (15). The mechanical part of the drive contains the Induction Motor and a loading DC motor. The experimental setup includes a fully digital controlled IGBT inverter with key parameter of induction motor is shown in Appendix.



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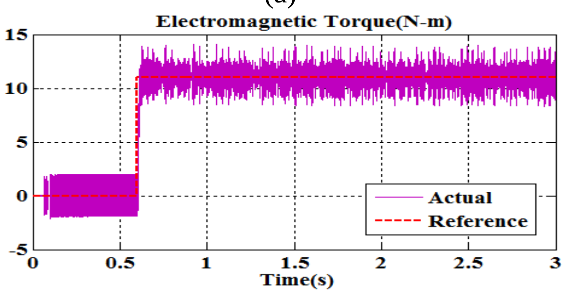
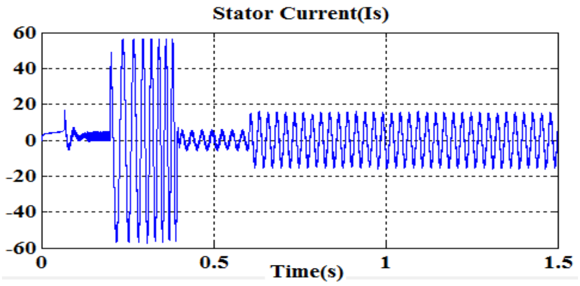
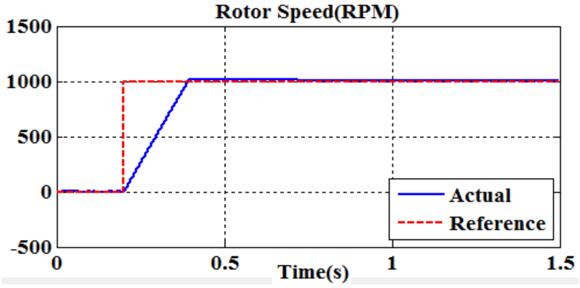


(b)

Fig.(8) Low Speed Operation a) Rotor Speed b) Torque



(a)



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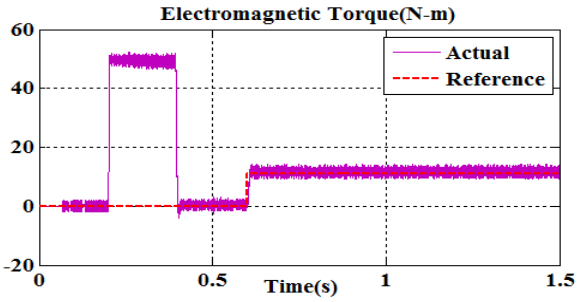
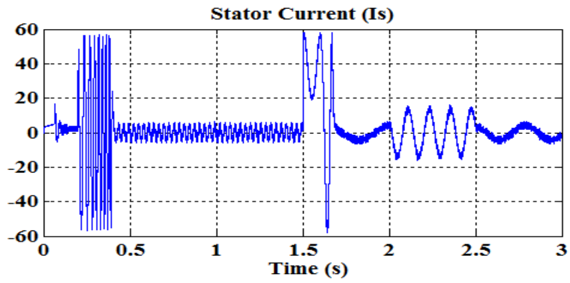


(c)

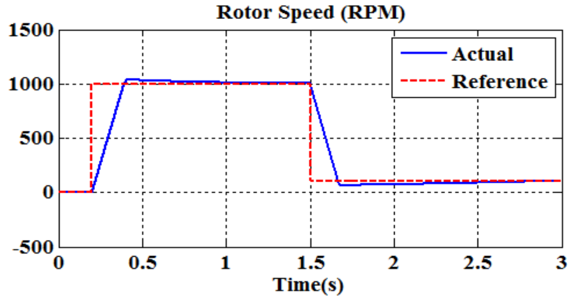
Fig.(9) Simulation Results – Constant Speed MRAS control with stator resistance compensation.
a) Stator Current b) Rotor Speed (0-1000rpm) c) Torque

The control scheme has been implemented on a 150 MHz fixed point TMS320F2812 DSP from Texas Instruments incorporated. The PWM pulse generator was generated by TMS320F2812 which were fed into gate drives of 3 phase current source inverter through a processing card.

The experimental results of proposed MRAS based torque estimator was investigated under constant speed, variable speed and zero speed operating condition with full load torque. The performance of Induction Motor drive was initially tested with speed of 1000 rpm and rated torque 10 N-m applied at 0.6 sec as shown in Fig. (16). Fig (17) shows that the test under variable speed from 0-1000-100 rpm and load was applied at 2 sec. From the results indicates that the rotor speed reaches its reference speed is faster and ripples content in torque is considerably reduced.



(a)



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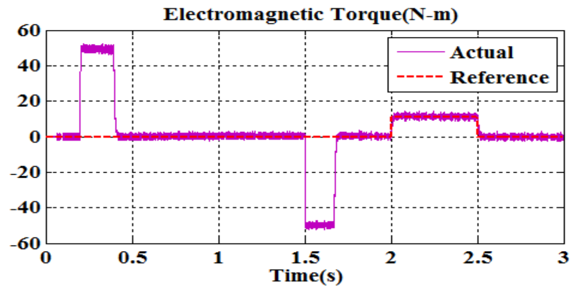
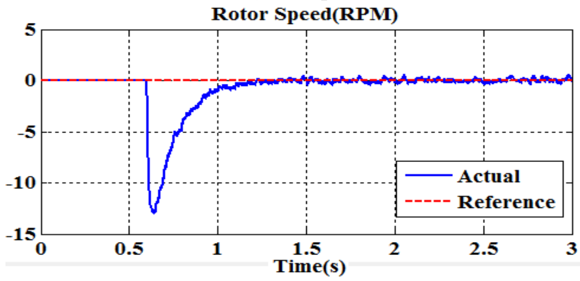
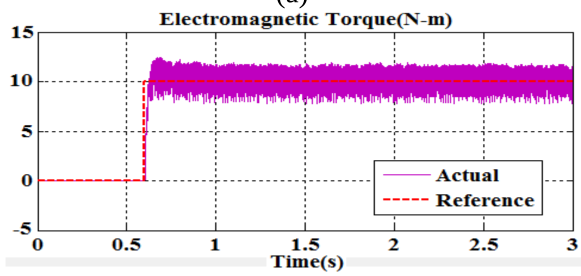


(c)

Fig (10) Simulation Results - Variable Speed MRAS control with stator resistance compensation.
a) Stator Current b) Rotor Speed (0-1000rpm) c) Torque

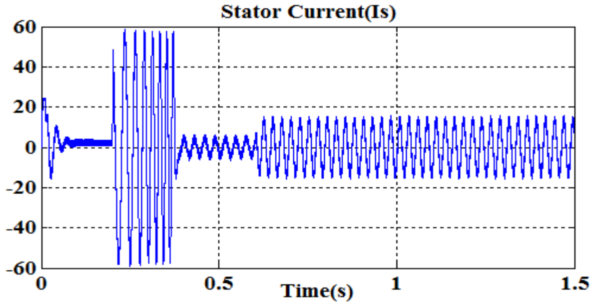


(a)

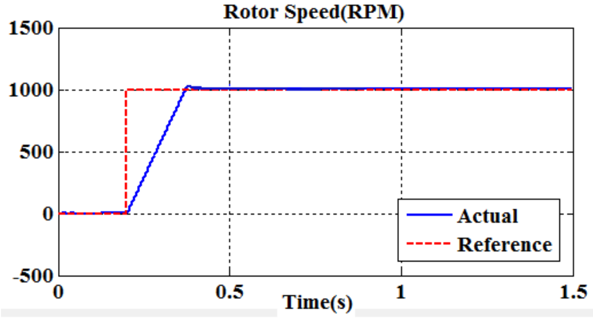


(b)

Fig. (11) Low Speed Operation
(MRAS with stator resistance compensation)
a) Rotor Speed b) Torque



(a)



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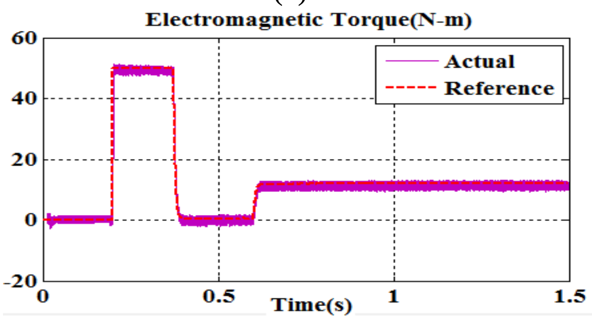
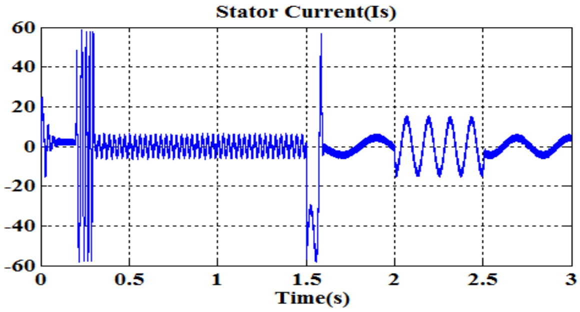
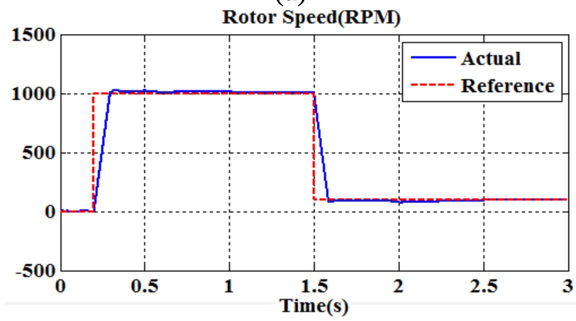


(c)

Fig (12) Simulation Results – Constant Speed Proposed MRAS based control
a) Stator Current b) Rotor Speed (0-1000rpm)
c) Torque



(a)



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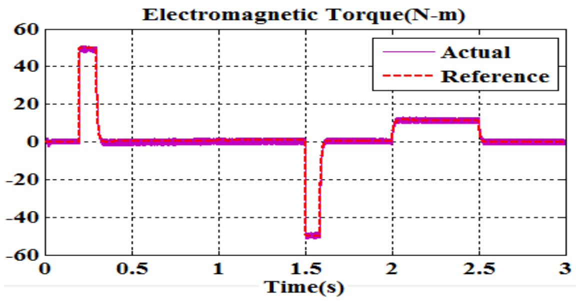
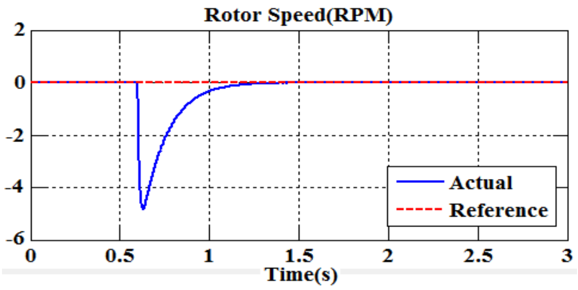
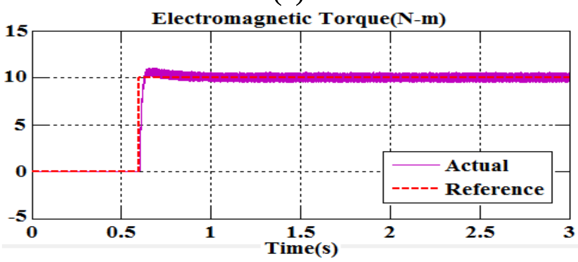


(c)

Fig (14) Simulation Results – Variable Speed Proposed MRAS based control
a) Stator Current b) Rotor Speed (0-1000 – 0 rpm)
c) Torque



(a)



(b)

Fig.(13) Low Speed Operation (proposed method)
a) Rotor Speed b) Torque

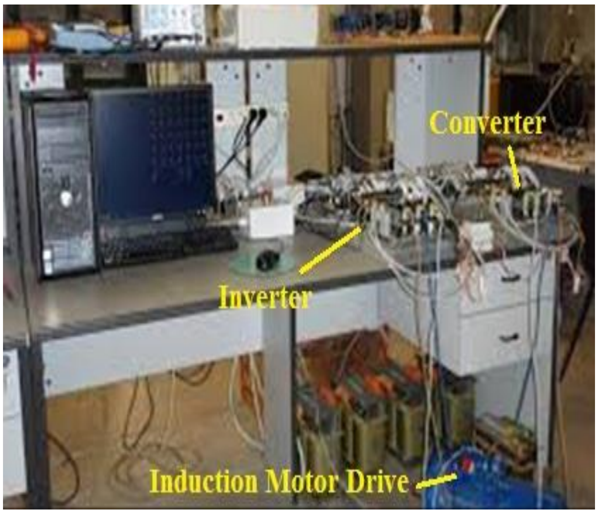


Fig. (15) Experimental setup

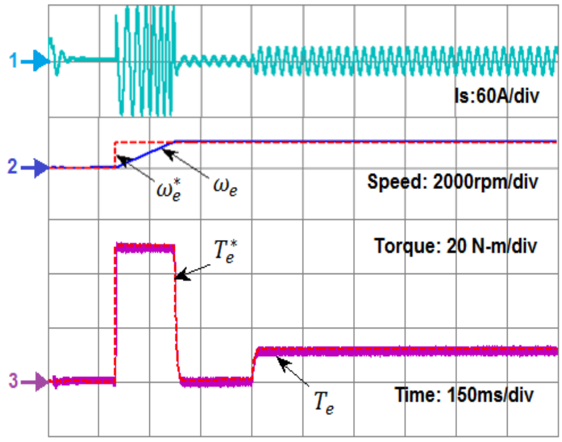


Fig.(16) Experimental result- constant speed

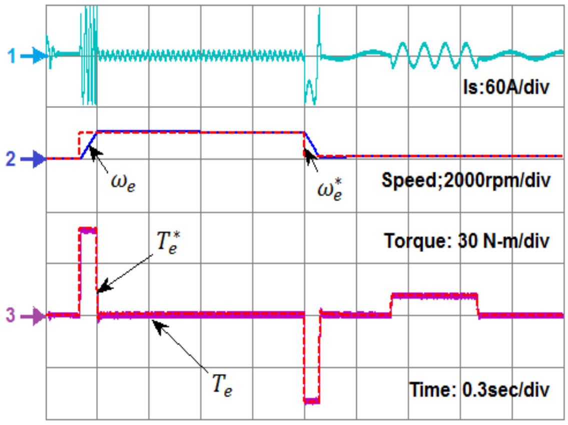


Fig.(17) Experimental result- Variable speed

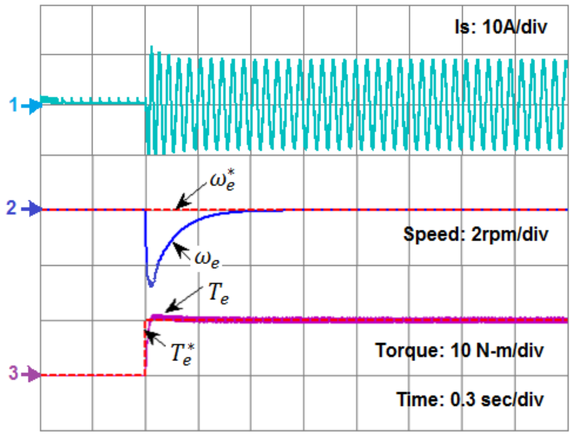


Fig.(18) Experimental result- Zero speed

The performance of under zero speed operation is shown in Fig (18) and load was applied at 0.6 sec. Speed drop has been reduced 3 rpm due to sudden application of load torque in proposed method. The experimental results prove that a proposed system of MRAS based torque estimator performed well for all kind of speed operation.

8. Conclusions

Proposed method of a novel MRAS based torque estimator that enables parallel estimation of torque and rotor speed with stator resistance compensation has been implemented to CSI fed FOC induction motor drive. The present method can directly establish an effective stator and rotor flux to induce the desired torque. The rotor speed has been estimated by using load torque feed forward control. The structure of the estimator is derived using hyper stability theory available within the standard rotor flux based MRAS technique. The instantaneous phase position of the two rotor fluxes estimates the torque. 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 based torque estimator.

Appendix

Induction motor parameters	
Rated Power	3 hp
Rated Voltage	460 V
Stator Resistance	0.087 Ω
Rotor Resistance	0.228 Ω
Stator Inductance	35.5 mH
Rotor Inductance	35.5 mH
Mutual Inductance	34.7 mH
Moment of inertia	1.662 kg.m^2
Friction co efficient	0.1 N.m.s/rad
Number of poles	4
Line side Capacitor	500 µF
Inverter side Capacitor	500 µF
DC inductance	35mH

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