Robust MRAS Based Sensorless Rotor Speed Measurement of Induction Motor against Variations in Stator Resistance Using Combination of Back Emf and Reactive Power Methods

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List of symbols

L_m	Magnetizing inductance (H)
L_r	Rotor self leakage inductance (H)
L_s	Stator self leakage inductance (H)
L_{sl}	Stator leakage inductance (H)
L_{rl}	Rotor leakage inductance (H)
$\sigma = 1 - L_m^2/(L_s L_r)$	Leakage coefficient
p_p	Number of pole pairs
T_l	Load torque (Nm),
T_e	Electromagnetic torque (Nm)
R_s	Stator resistance (Ω)
R_r	Rotor resistance (Ω)
ω_e	Synchronous speed (rad/sec),
ω_{sl}	Slip speed (rad/sec)
$\omega_r = p_p\,\omega_m$	Rotor electrical speed (rad/sec)
$\omega_m = \dot{\theta}_m$	Rotor Mechanical speed (rad/sec)
J	Moment of inertia (N-m/rad/sec^2)
B	Viscous friction coefficient

I. Introduction

INDUCTION motors (IM) with a squirrel cage rotor are the most widely used machines at fixed speed because of their simplicity, ruggedness, efficiency, compactness and reliability. Due to their highly coupled non-linear structure, induction motors were dedicated for years mainly in unregulated drives. The idea of induction motor control with the principle of Field Oriented Control (FOC) was a big breakthrough which enabled a decoupled control of rotor flux and electromagnetic torque.

The MRAS speed estimators are the most attractive approaches due to their design simplicity Due to the variations of the temperature the detuning of R_S causes the rotor speed (ω_r) and torque response to deteriorate at low speed. Therefore, the simultaneous estimation of ω_r and R_S is essential [7].

During the R_S identification time interval, the drive is without the information of speed. The steady state condition is required for R_S estimation. The reactive power method as a single entity has the disadvantage of θ_S calculation for rotor flux (Ψ_r) estimation.

This paper presents a new MRAS estimator. In the proposed structure U_S – I_S rotor flux estimator serves as the reference model for ω_R estimation with I_S ω_R estimator as an adjustable model. The adaptive model does not include the parameter R_S but could be seen with reference model only. The proposed algorithm can be readily implemented in a vector control Sensorless induction motor. Experimental results show the effectiveness of the proposed MRAS observers.

II. INDUCTION MOTOR MATHEMATICAL MODEL

An IM model in the d–q synchronously rotating frame, under commonly used assumptions, can be expressed as

$$i_{dr} = -\left(\frac{R_s}{\sigma L_s} + \frac{R_r L_m^2}{\sigma L_s L_r^2}\right) I_{DS} + \omega_e I_{QS} + \frac{R_r L_m}{\sigma L_s L_r^2}\Psi_{rd} + \frac{\omega_r L_m}{\sigma L_s L_r}\Psi_{rq} + \frac{1}{\sigma L_s}U_{DS} \quad (1)$$

$$i_{qs} = -\left(\frac{R_s}{\sigma L_s} + \frac{R_r L_m^2}{\sigma L_s L_r^2}\right) I_{QS} + \omega_e I_{DS} + \frac{R_r L_m}{\sigma L_s L_r^2}\Psi_{rq} + \frac{\omega_r L_m}{\sigma L_s L_r}\Psi_{rd} + \frac{1}{\sigma L_s}U_{QS} \quad (2)$$

$$\Psi_{rd} = \frac{R_r L_m}{L_r} I_{DS} + \frac{R_r}{L_r}\Psi_{rd} + (\omega_e - \omega_r)\Psi_{rq} \quad (3)$$

$$\Psi_{rq} = \frac{R_r L_m}{L_r} I_{QS} - \frac{R_r}{L_r}\Psi_{rq} - (\omega_e - \omega_r)\Psi_{rd} \quad (4)$$

$$J\ddot{\theta} + B\theta_m' + T_l = T_e \quad (5)$$

$$T_e = \frac{3P_p L_m}{2L_r}(I_{qs}\Psi_{rd} - I_{ds}\Psi_{rq}) \quad (6)$$

where u_{ds} and u_{qs} are the *d–q* components of stator voltage, respectively; i_{ds} and i_{qs} are the stator current components; Φ_{dr} and Φ_{qr} are the rotor flux components.

A sixth-order nonlinear model describes the IM in the *d–q* system.

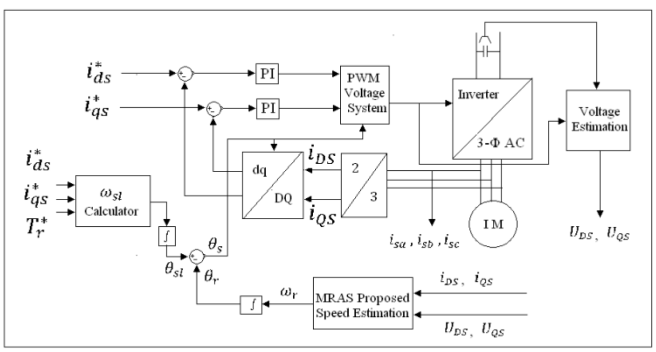


Fig.1.Block diagram of proposed robust control system using the simplified rotor flux oriented vector control of an Induction Motor

The vector control principle, usually implemented by rotor flux-oriented control, ensures decoupling of torque control and rotor flux control. Rotor flux is oriented toward the *d*-axis

$$\Psi_{rd} = \Psi_r, \qquad \Psi_{rq} = \dot{\Psi}_{rq} = 0 \quad (7)$$

Using (7), (3) and (4) are reduced to

$$T_r\dot{\Psi}_r + \Psi_r = L_m i_{ds} \quad (8)$$

$$\omega_s = \omega_e - \omega_r = \omega_e - p_p m = L_m i_{qs}/(T_r\Psi_r) \quad (9)$$

defining rotor flux dynamics and slip frequency [3]. $T_r = L_r/R_r$ is a rotor time constant. Rotor flux is generated only by the flux current component i_{ds}. Since the rotor flux should be constant, the d-axis current controller should ensure that i_{ds} keeps a desired constant value i_{ds}*. In steady state, the rotor flux is given by

$$\Psi_r = L_m i_{ds}^* \quad (10)$$

Substituting (7) and (10) into (6), electromagnetic torque becomes

$$T_e = k_t i_{qs}, \qquad k_t = \left(\frac{3p_p}{2}\right)\left(\frac{L_m^2}{L_r}\right) i_{ds}^* \quad (11)$$

As a result, the electromagnetic torque is linearly dependent on the torque current component I_{QS}, indicating that both rotor flux and electromagnetic torque can be controlled separately.

In the proposed IM control scheme, shown in Fig.1, there is only a flux current PI controller. Torque current controller and decoupling circuits are excluded.

III. Speed Tuning Signal

In the new scheme, the speed tuning signal is deliberately chosen to be $Im(\Delta\bar{e}\,\bar{i_s})$, where $\Delta\bar{e} = \bar{e} - \hat{\bar{e}}$ and $\bar{e}, \hat{\bar{e}}$ are the space vectors of the back e.m.f.s in the reference model and adaptive model respectively. It follows that $Im(\Delta\bar{e}\,\bar{i_s}) = \bar{i_s} \times \Delta\bar{e} = \bar{i_s} \times \bar{e} - \bar{i_s} \times \hat{\bar{e}}$ and $\bar{e} = e_d + je_q$, $\bar{U_s} = U_{DS} + jU_{QS}$, $\bar{i_s} = i_{DS} + ji_{QS}$,

$$y = \bar{i_s} \times \bar{e} = \bar{i_s} \times \left(\bar{U_s} - L_s' \frac{d\bar{i_s}}{dt}\right) \quad (12\text{ a})$$

is obtained, which is the output of the reference model. It can be seen that this does not contain the stator resistance and this is why y has been chosen to be a component of the speed tuning signal. In other words, since the stator-voltage space vector $(\bar{U_s})$ is equal to the sum of the stator ohmic voltage drop ($R_s\,\bar{i_s}$) plus $L_s'\,d\bar{i_s}/dt$, plus the back e.m.f. $\bar{e} = (L_m/L_r)d\bar{\Psi_r}/dt$, therefore the vectorial product $\bar{i_s} \times \bar{U_s}$, does not contain the stator resistance and takes the form $\bar{i_s} \times \bar{U_s} = \bar{i_s} \times L_s' d\bar{i_s}/dt + \bar{i_s} \times \bar{e}$, and this gives eqn (12 a) as expected. The first term on the right-hand side of eqn (12 a) is $\bar{i_s} \times \bar{U_s}$, the reactive input power.

Similarly to the other two schemes discussed in the previous two sections, the stator voltage components U_{DS}, U_{QS} can be obtained from the monitored line voltages, or in an inverter-fed induction motor drive, they can be reconstructed from the inverter switching states and the monitored value of the d.c. link voltage.

$$\hat{e_d} = \frac{L_m}{L_r}\frac{d\Psi_{rd}}{dt} = \frac{L_m}{L_r}\frac{(L_m i_{DS} - \Psi_{rd} - \omega_r T_r \Psi_{rq})}{T_r} \quad (12\text{ b})$$

$$\hat{e_q} = \frac{L_m}{L_r}\frac{d\Psi_{rq}}{dt} = \frac{L_m}{L_r}\frac{(L_m i_{QS} - \Psi_{rq} - \omega_r T_r \Psi_{rd})}{T_r} \quad (12\text{ c})$$

The output of the adaptive model is obtained by considering eqns (12 b), (12 c) and $\hat{\bar{e}} = e_d + je_q$, as follows:

$$\hat{y} = \bar{i_s} \times \hat{\bar{e}} = \bar{i_s} \times \frac{L_m}{L_r}\left[\frac{L_m}{T_r}\bar{i_s} + \frac{\Psi_r'(j\omega_r - 1)}{T_r}\right]$$
$$= \frac{L_m}{L_r}\left[\frac{1}{T_r}\bar{\Psi_r'} \times \bar{i_s} + \omega_r(\bar{i_s} \times j\bar{\Psi_r'})\right] \quad (13)$$

Fig. 1shows the schematic of the rotor speed observer using the speed tuning signal $\varepsilon_{\Delta e} = Im(\bar{e}\bar{i_s})$.The reference model is represented by eqn (14) and the adaptive model by eqn (15).

A. Reference Model

The reference model is based on the following equation.

$$y = \bar{i_s} \times \bar{e} = U_{QS} i_{DS} - U_{DS} i_{QS} - L_s'\left[i_{DS}\frac{di_{QS}}{dt} - i_{QS}\frac{di_{DS}}{dt}\right] \quad (14)$$

B. Adaptive Model

$$\hat{y} = \bar{i_s} \times \hat{\bar{e}} = \frac{L_m}{L_r}\left[i_{QS} - \Psi_{rq} i_{DS}) + \omega_r(\Psi_{rd} i_{DS} - \Psi_{rq} i_{QS})\right] \quad (15)$$

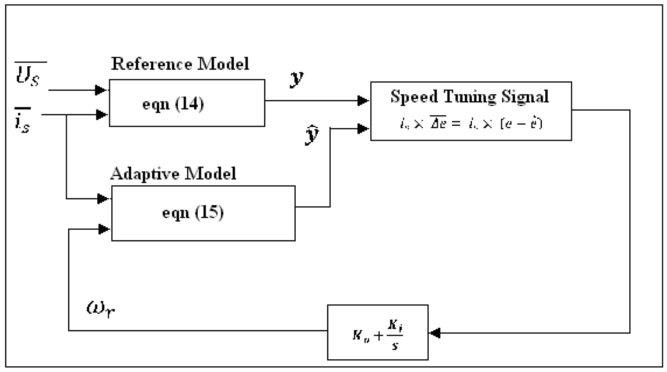


Fig.2 Block diagram of Proposed MRAS Scheme for Speed Estimation

Where Ψ_{rd} and Ψ_{rq} are the estimated values from the model itself instead of deploying separate flux calculator for the calculation of the same.

IV. FLUX ESTIMATOR

The block diagram in Fig. 3 explains the estimation of flux with the help of the equations from eq. (14) to eq. (17)

$$L'_S = \sigma L_S = 1 - \frac{L_m^2}{L_s L_r} T_s \qquad (16)$$

$$\Psi'_r = \frac{L_r}{L_m}(\Psi_s - L'_s i_s) \qquad (17)$$

$$T_r = \frac{L_r}{R_r} \qquad (18)$$

$$\Psi'_r = \frac{L_r}{L_m}\left[\int\left(\overline{U_s} - R_s \overline{i_s}\right) dt - L'_s i_s\right] \qquad (19)$$

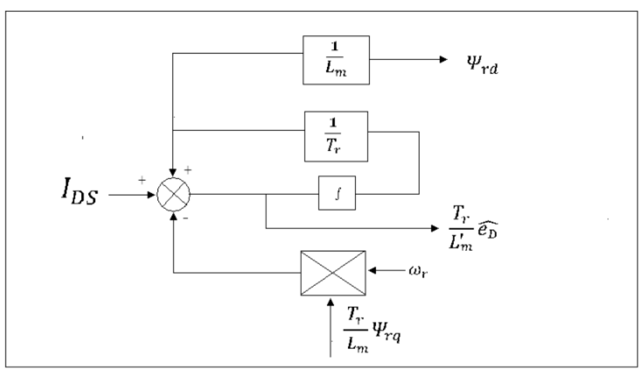


Fig.3 Block diagram of the Flux Estimator

Thus the flux is estimated with which the speed is estimated avoiding stator resistance, R_S [4]. The rotor speed estimation algorithm (adaptation mechanism) is chosen according to *popov's hyperstability* theory [9], eq. (18), whereby the transfer function matrix of the linear time invariant subsystem must be strictly positive real and the non-linear time varying feedback subsystem satisfies proportional and integral (PI) inequality according to which

$$\int V^T W \, dt \geq 0 \qquad (20)$$

in the time interval $[0,t_1] \in t_1 \geq 0$.

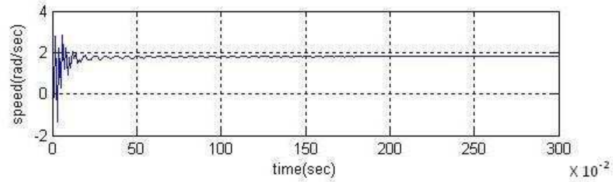
The application of the proposed theorem yields to contain a PI controller and the appropriate speed tuning signal in the MRAS system described.

V. SIMULATION

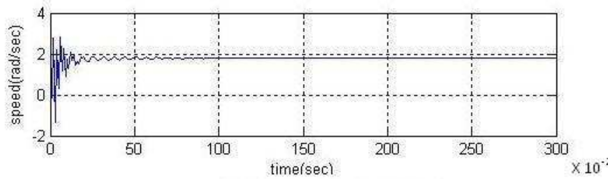
The performance of the proposed model of speed estimation is verified with simulation in Matlab 7 software.

VI. SIMULATION RESULTS

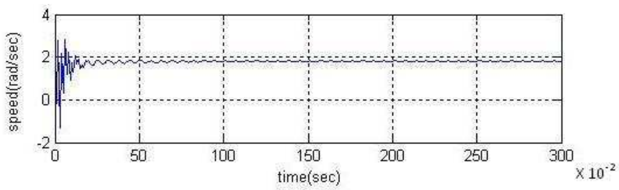
The simulation results in the evaluation of rotor speed response with the variations in the stator resistance. Fig (a), Fig (b) and Fig (c) shows the speed response when the current i_s is 0.1 A for the stator resistance of 10 ohms, 8 ohms and 12 ohms respectively. Fig (d), Fig (e) and Fig (f) shows the speed response when the current i_s is 0.2 A for the stator resistance is 10 ohms, 8 ohms and 12 ohms respectively. In all the combinations, the speed is expected to be constant irrespective to the variations in stator resistance.



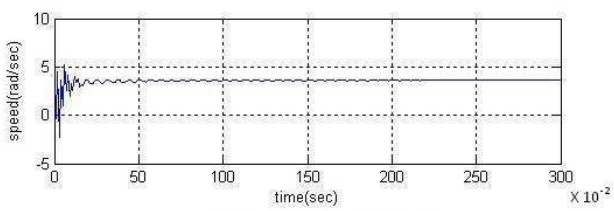
fig(a) for i=0.1A and Rs=10ohms



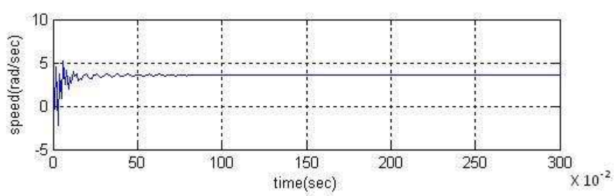
fig(b) for i=0.1A and Rs=8ohms



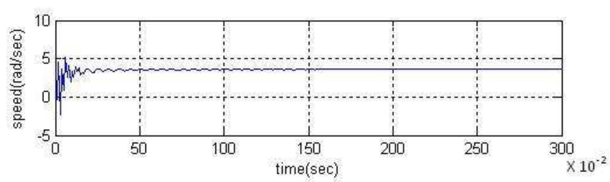
fig(c) for i=0.1A and Rs=12ohms



fig(d) for i=0.2A and Rs=10ohms



fig(e) for i=0.2A and Rs=8ohms



fig(f) for i=0.2A and Rs=12ohms

Fig. (g) and Fig. (i) shows I_{sD} and I_{sQ} respectively, when I=0.1A and Fig. (h) and Fig. (j) shows I_{sD} and I_{sQ} respectively, when I=0.2A.

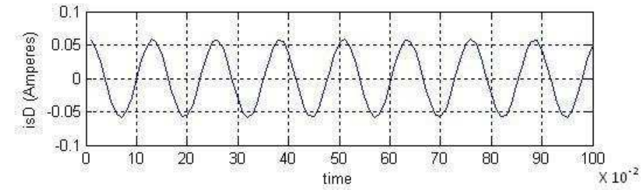


Fig.(g) isD at 0.1A

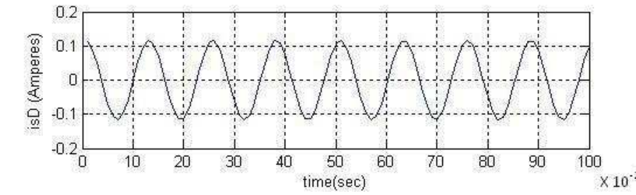


Fig.(h) isD at 0.2A

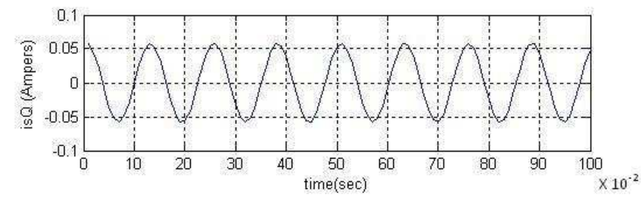


Fig.(i) isQ at 0.1A

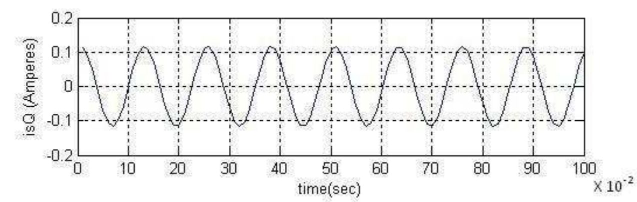


Fig.(j) isQ at 0.2A

VII. CONCLUSION

As proved from above that, when the rotor speed to be estimated is changed in the adaptive model in such a way that the difference between the output of the reference model and the adaptive model is zero, then the estimated rotor speed is equal to the actual rotor speed. The error signal actuates the rotor speed identification algorithm, which makes the error converge asymptotically to zero.

There is a problem of speed calculation especially at low speeds with back emf method and there is a requirement of synchronous reference frame with reactive power method [2]. The Present model which takes the advantages of both the methods i.e., back emf method that does not require synchronous reference frame and reactive power method for stable speed estimation especially at low speeds.

As verified from results, the time response of the speed estimation is settling to 90 % of final value in less than 0.25 seconds.

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Induction Motor Data:								
U_n [V]	I_n [A]	P_n [W]	T_n [Nm]	L_s [H]	L_r [H]	M_n [H]	R_{sm} [Ω]	R_{rm} [Ω]
380	2.1	750	5	0.464	0.461	0.421	10	6.3