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Dynamic Simulation of Robust Sensorless Speed Measurement in IM Using MRAC against Variations in Stator Resistance and Rotor-Time Constant

Srikanth Mandarapu, Sreedhar Lolla, Madhu Chandra Popuri

Abstract—This paper proposes a Model Reference Adaptive Control (MRAC) which makes use of both back EMF and Reactive Power methods for sensorless rotor speed measurement against variations in rotor time constant in addition to the variations in stator resistance. The adjustable model makes use of these two methodologies eliminates the need to calculate rotor flux, thus avoiding the requirement of synchronously rotating reference angle and the stable speed can also be estimated even at low speeds. The effectiveness of the proposed model is proved with extensive computer simulation.

Index Terms— back emf method, reactive power method, Rotor Speed, Sensorless Control, Stator Resistance.

List of symbols

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

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.

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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 [5].

The MRAC speed estimators are the most attractive approaches due to their design simplicity. Due to the variations of the temperature the detuning of R_S, $T_r = L_r/R_r$ causes the rotor speed (ω_r) and torque response to deteriorate at low speed, where T_r is a heat dependent [7]. Therefore, the simultaneous estimation of ω_r and R_S is essential.

The drive is without the information of speed during the R_S identification time interval. For R_S estimation the steady state condition is required. The reactive power method as a single entity has the disadvantage of θ_S calculation for rotor flux (Ψ_r) estimation [2].

This paper presents a new MRAC estimator. In the proposed structure $U_S - I_S$ rotor flux estimator serves as the reference model for ω_R estimation with $I_S\,\omega_R$ estimator as an adjustable model. The adaptive model does not include the parameter R_S and T_r but could be seen with reference model only. The proposed algorithm can readily be implemented in a vector control Sensorless induction motor [1]. Simulation results show the effectiveness of the proposed MRAC observers.

II. MATHEMATICAL MODEL OF IM

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

$$\dot{i}_{ds} = -\left(\frac{R_s}{\sigma L_s} + \frac{L_m^2}{\sigma L_s L_r T_r}\right) I_{DS} + \omega_e I_{QS} + \frac{L_m}{\sigma L_s L_r T_r}\Psi_{rd} + \frac{\omega_r L_m}{\sigma L_s L_r}\Psi_{rq} + \frac{1}{\sigma L_s} U_{DS} \quad (1)$$

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

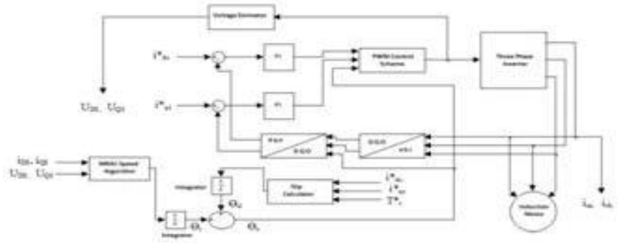

Fig.1.Block diagram of proposed robust control system using the simplified rotor flux oriented vector control of an Induction Motor

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A sixth-order non-linear model describes the IM in the d–q system.

$$\dot{\Psi}_{rd} = \frac{L_m}{T_r} I_{DS} + \frac{\Psi_{rd}}{T_r} + (\omega_e - \omega_r)\Psi_{rq} \quad (3)$$

$$\dot{\Psi}_{rq} = \frac{L_m}{T_r} I_{QS} - \frac{\Psi_{rq}}{T_r} - (\omega_e - \omega_r)\Psi_{rd} \quad (4)$$

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

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

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.

The vector control principle, usually implemented by rotorflux-oriented control, ensures decoupling of torque control androtor flux control [3]. Rotor flux is oriented toward the d-axis

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

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. $T_r = L_r/R_r$ is a rotor time constant. Rotor flux is generated only by the fluxcurrent 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

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

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 ALGORITHM

In the new scheme, the speed tuning signal is deliberately chosen to be $Im(\Delta\bar{e}\bar{i}_s)$, where $\Delta\bar{e} = \bar{e} - \hat{e}$ and $\bar{e}, \hat{e}$ are the space vectors of the back e.m.f.s in the reference model and adaptive model respectively. It follows that

$$Im(\Delta\bar{e}\bar{i}_s) = \bar{i}_s \times \Delta\bar{e} = \bar{i}_s \times \bar{e} - \bar{i}_s \times \hat{e} \text{ and}$$
$$\bar{e} = e_d + je_q, \bar{U}_s = U_{DS} + jU_{QS}, \bar{i}_s = i_{DS} + ji_{QS},$$

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

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 equation (12 a) as expected. The first term on the right-hand side of equation (12 a) is $\bar{i}_s \times \bar{U}_s$, the reactive input power.

Similarly, 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.

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

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

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

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

It could be observed that the adaptive model is a function of ω_r and T_r which will not be observed with the reference model. The reference model is represented by equations (14) and the adaptive model by equation (15) [5].

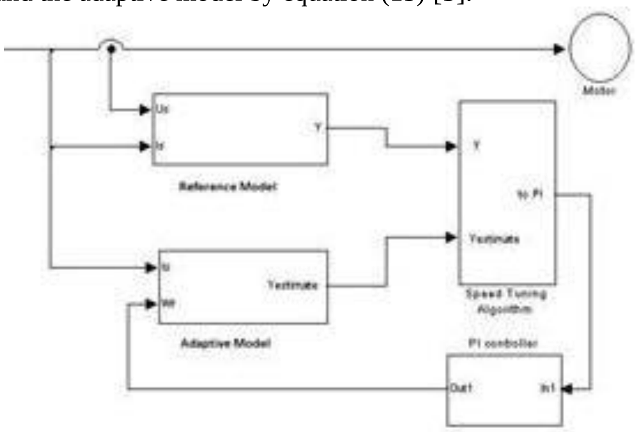

Fig.2 Block diagram of Proposed MRAC Scheme for Speed Estimation

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*

$$\hat{y} = \bar{i}_s \times \hat{e} = \frac{L_m}{L_r}\begin{bmatrix} i_{QS} - \Psi_{rq}i_{DS}) \\ +\omega_r(\Psi_{rd}i_{DS} - \Psi_{rq}i_{QS}) \end{bmatrix} \quad (15)$$

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 ESTIMATION ALGORITHM

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

$$L_S^{'} = \sigma L_S = 1 - \frac{L_m^2}{L_s L_r} T_s \tag{16}$$

$$\Psi_r^{'} = \frac{L_r}{L_m} (\Psi_s - L_s^{'} i_s) \tag{17}$$

$$T_r = \frac{L_r}{R_r} \tag{18}$$

$$\Psi_r' = \frac{L_r}{L_m} \left[\int \left(\overline{U_s} - R_s \overline{i_s} \right) dt - L_s' i_s \right] \tag{19}$$

Thus the flux is estimated with which the speed is estimated avoiding stator resistance, R_S and rotor time constant, T_r. The rotor speed estimation algorithm (adaptation mechanism) is chosen according to *Popov's hyperstability* theory, eq. (18) [2], 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 in the time interval $[0,t_1] \in t_1 \geq 0$.

$$\int V^T W \, dt \geq 0 \tag{20}$$

A PI controller is obtained from the proposed scheme from which the appropriate speed tuning signal in the MRAC system is designed.

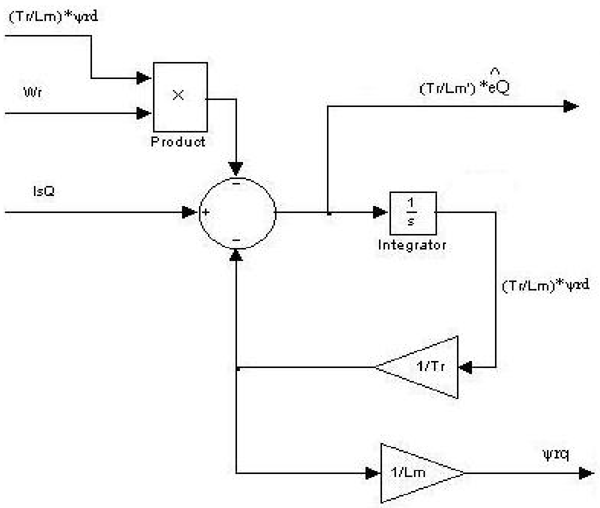

Fig.3 Block diagram of the Flux Estimator

V. SIMULATION

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

VI. SIMULATION RESULTS

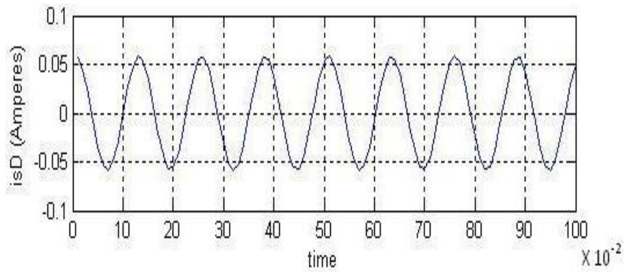

Fig. 4 (a) i_{sD} = 0.1 A

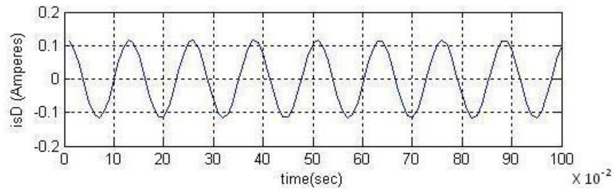

Fig. 4 (b) i_{sD} = 0.2 A

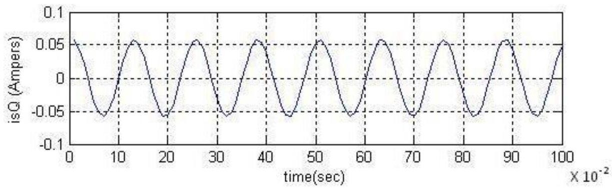

Fig. 4 (c) i_{sQ} = 0.1 A

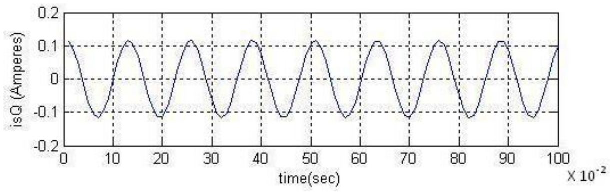

Fig. 4 (d) i_{sQ} = 0.2 A

The simulation results in the evaluation of rotor speed response with the variations in the stator resistance. Fig. 4(a) and Fig. 4(b) shows I_{sD} and I_{sQ} respectively, when I = 0.1 A and Fig. 4(c) and Fig. 4(d) shows I_{sD} and I_{sQ} respectively, when I = 0.2 A.

Fig 4(e), Fig 4(f) and Fig 4(g) 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 for various rotor time constants

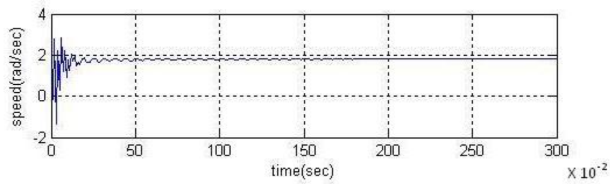

Fig. 4 (e) i = 0.1 A, R_s = 10 Ω and T_r = 0.0732 s

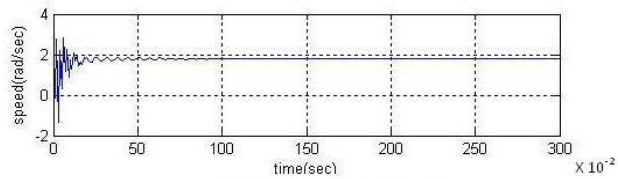

Fig. 4 (f) i = 0.1 A, R_s = 8 Ω and T_r = 0.0586 s

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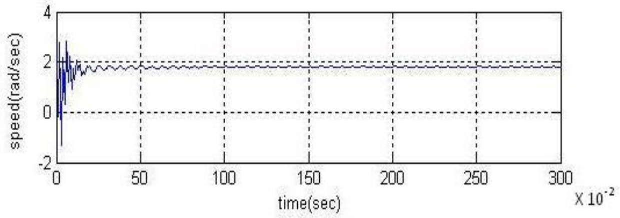

Fig. 4 (g) i = 0.1 A, R_s = 12 Ω and T_r = 0.0878 s

Fig 4(h), Fig 4(i) and Fig 4(j) 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 also for different rotor time constants. In all the combinations, the speed is expected to be constant irrespective to the variations in stator resistance.

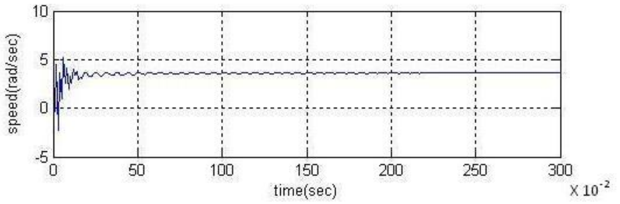

Fig. 4 (h) i = 0.2 A, R_s = 10 Ω and T_r = 0.0732 s

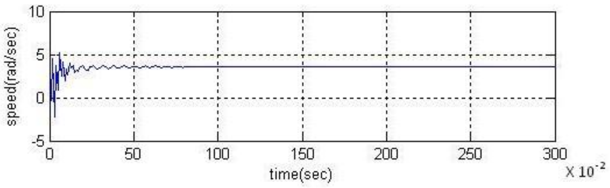

Fig. 4 (i) i = 0.2 A, R_s = 8 Ω and T_r = 0.0586 s

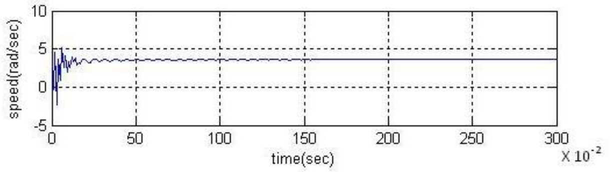

Fig. 4 (j) i = 0.2 A, R_s = 12 Ω and T_r = 0.0878 s

VII. CONCLUSION

The adaptive model is a function of ω_r and T_r. These parameters are not observed with the reference model. The error signal which is the difference of the outputs of the adaptive and reference models actuates the rotor speed identification algorithm, which makes the error converge asymptotically to zero. Thus, the estimated rotor speed is made equal to the actual rotor speed.

There is a requirement of synchronous reference frame with reactive power method and there is a problem of speed calculation especially at low speeds with back emf method. The present model takes the advantages of both the methods i.e., back emf method that does not require synchronous reference frame, and the reactive power method for stable speed estimation especially at low speeds, helps greatly in converging giving a better response.

It is worth mentioning that, whilst in [5] where the variation in R_S only was considered, a similar response of less than 0.25sec has been obtained, in spite of addition of variations in T_r.

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