D.Sleeva Reddy, K. Lakshmi Prasad Reddy, M.Vijaya Kumar / International Journal of Engineering Research and Applications (IJERA) ISSN: 2248-9622 www.ijera.com
Vol. 2, Issue 6, November- December 2012, pp.172-179

Online Estimation Of Rotor Time Constant And Speed For Vector Controlled Induction Motor Drive With Model Reference Adaptive Controller (MRAC)

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Abstract:

In this paper, a detailed study on the Model Reference Adaptive Controller is presented for online estimation of Rotor Time constant and speed for indirect field oriented control Induction Motor Drive with MRAC. This MRAC consists of two models. The first is Reference Model and other one is Adjustable Model. One model is independent of slip speed and other one is dependent on slip speed. The MRAC designed is immune to stator resistance. The design of MRAC is based on Reactive Power concept. Moreover, the unique formation of the MRAC with the instantaneous and steady-state reactive power completely eliminates the requirement of any flux estimation in the process of computation. Thus, the method is less sensitive to integrator-related problems like drift and saturation. This also makes the estimation at or near zero speed quite accurate. The simulation results obtained are satisfactory and are discussed in this paper to highlight the proposed approach. The simulation work is performed in MATLAB/ SIMULINK environment.

Key words: ***MRAC, Induction Motor drive, drift and saturation***

1. INTRODUCTION

The development of Hybrid systems is the reduction of consumption and emission by combining the advantages of combustion engines and electrical and other machinery. By embedding electrical machines within railway traction or ship propulsion, several problems arise regarding their command. The control is realized through a suitable action on their command.

The vector control allows having a decoupling between torque and flux of the machine and consequently dynamic performance similar to those of a DC machine are achieved. Vector control is classified into two types. Namely direct or feedback field oriented control and indirect or feed forward field oriented control. However, feed forward field oriented control which requires rotor resistance, makes this scheme dependent on machine parameters. Of all the parameters, the rotor resistance undergoes considerable variation and if care is not taken to compensate for the change, the flux orientation is lost, resulting in coupling between the *d*- and *q*-axes variables. As is well known, the coupling makes the performance of the drive system sluggish. Much attention is focused to enforce field orientation through online estimation of the machine parameters.

Many online parameter estimation schemes are developed so far.
They are broadly classified as

a. Signal injection based technique
b. Observer based method
c. Model reference adaptive system
d. Other methods

The Model reference adaptive system is one of the methods for online estimation of Rotor time constant. This is an approach that has attracted most of the attention due to its relatively simple implementation requirements. The basic idea is that one quantity can be calculated in two different ways. The first value is calculated from references inside the control system. The second value is calculated from measured signals. One of the two values is independent of the rotor resistance (rotor time constant). The difference between the two is an error signal, whose existence is assigned entirely to the error in rotor resistance used in the control system. The error signal is used to drive an adaptive mechanism (PI or I controller) which provides correction of the rotor resistance. Any method that belongs to this group is based on utilization of the machine model and its accuracy is therefore heavily dependent on the accuracy of the applied model. The number of methods that belong to this group is vast and they primarily differ with respect to which quantity is selected for adaptation purposes. Reactive power-based method is not dependent on stator resistance at all and is probably the most frequently applied approach.

In this paper, the performance of a modified reactive power based MRAC is investigated in detail for online estimation of rotor time constant. The MRAC is formulated in such a way that rotor flux estimation is not required. It is important to note that [5] and [6] have reviewed such MRAC-based schemes; however, a detailed study including stability and sensitivity analysis were not available. Most of the MRAC-based systems [13]–[15] require flux estimation. Therefore, they suffer from integrator-

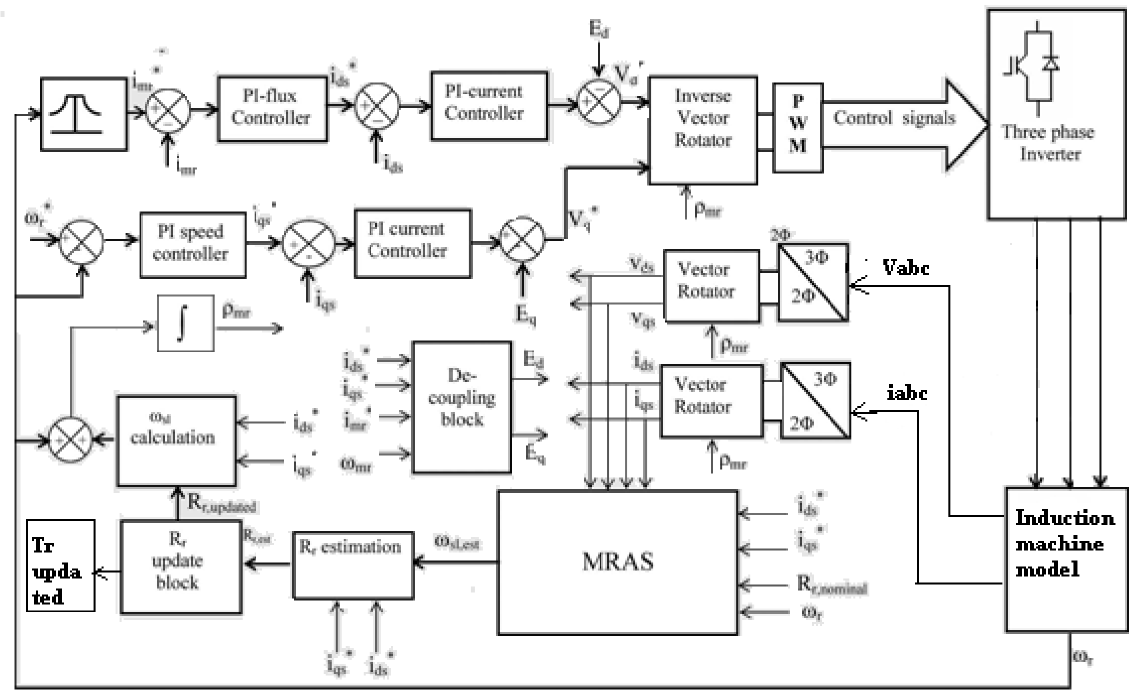


Fig. 3. Block diagram of the MRAC-based rotor time constant estimation for IFOC IM drive

related problems at low speed and achieve less accuracy in estimation. The uniqueness of the MRAC under investigation is that the instantaneous reactive power is used in the reference model, whereas steady state reactive power is used in the adjustable model. The scheme is simulated in MATLAB/SIMULINK environment, and estimated the performance of proposed method for parameter estimation.

This paper is organized as follows. In section II the design and development of proposed scheme is discussed. Section III & IV provides simulation results. Conclusions are given in section

II. PROPOSED SCHEME

a. Basic structure of MRAC

In this paper MRAC is designed on the basis of reactive power, because reactive power based MRAC is immune to stator resistance. In the proposed MRAC (Fig. 1), the reference model and adjustable model compute instantaneous reactive power (Qref) and steady-state reactive power (Qest), respectively. The reference model is independent of slip speed (ωsl) whereas the adjustable model depends on ωsl.. The error signal ($\varepsilon = Q$ref $-$ Qest) is fed to the adaptation mechanism block, which yields estimated slip speed (ωsl,est). Rotor resistance (Rr) is then computed from ωsl,est. Fig. 2 is the modified scheme to reduce the detuning effect of the adaptation mechanism during transient. The complete drive including the estimation mechanism is available in Fig. 3. A rotor resistance update block is inserted in Fig. 2 to make the IFO-controller less sensitive to the dynamics of MRAC.

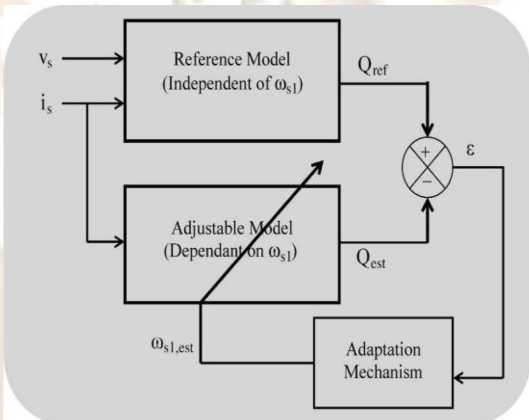


Fig 1. Basic Structure of MRAC

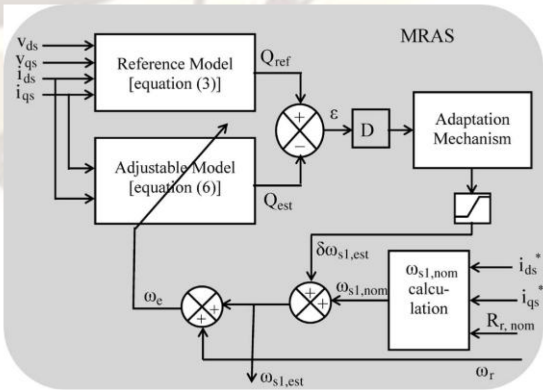


Fig 2. Modified structure of MRAC

b. Theoretical development of proposed scheme

The *d* and *q* axis voltages for IM referring to the synchronously rotating (ω_e) reference frame can be expressed

$$v_{ds} = R_s i_{ds} + \sigma l_s i'_{ds} + \frac{L_m}{L_r}\dot{\varphi}_{dr} - \sigma L_s \omega_e i_{qs} - \omega_e \frac{L_m}{L_r}\varphi_{qr} \quad (1)$$

$$v_{qs} = R_s i_{qs} + \sigma l_s i'_{qs} + \frac{L_m}{L_r}\dot{\varphi}_{qr} - \sigma L_s \omega_e i_{ds} + \omega_e \frac{L_m}{L_r}\varphi_{dr} \quad (2)$$

Where $\omega_e = \omega_r + \omega_{sl}$

The instantaneous reactive power (*Q*) can be expressed as

$$Q_1 = V_{qs} i_{ds} - V_{ds} i_{qs} \quad (3)$$

Substituting (1) and (2) in (3), the new expression of *Q* is

$$Q_2 = \sigma L_s[i'_{qs} i_{ds} - i'_{ds} i_{qs}] + \sigma L_s \omega_e - \frac{L_m}{L_r}[\dot{\varphi}_{dr} i_{qs} - \dot{\varphi}_{qr} i_{ds}] + \omega_e \frac{L_m}{L_r}[\varphi_{qr} i_{ds} + \varphi_{dr} i_{ds}] \quad (4)$$

It is worthwhile to mention that the above expressions of *Q* are free from stator resistance, which is a notable feature of any reactive power-based scheme.

In steady state the derivative terms are zero. Therefore, the expression of *Q* reduces to

$$Q_3 = \sigma L_s \omega_e [i_{ds}^2 + i_{qs}^2] + \frac{L_m}{L_r}\omega_e[\varphi_{qr} i_{qs} - \varphi_{dr} i_{ds}] \quad (5)$$

Substituting the condition $\psi dr = Lmids$ and $\psi qr = 0$ for the indirect field-oriented control (IFOC) IM drive in (5), the more simplified expression of *Q* is

$$Q_4 = \sigma L_s \omega_e [i_{ds}^2 + i_{qs}^2] + \omega_e \frac{L_m^2}{L_r} i_{ds}^2 \quad (6)$$

From the above expressions of *Q*, *Q*1 is unanimously chosen as the reference model as it does not comprise any slip-speed term. Out of the remaining expressions of *Q* (i.e., *Q*2, *Q*3 and *Q*4), *Q*4 may be used in the adjustable model as it does not contain a rotor flux and several derivative terms. Moreover, *Q*4 is dependent on slip speed.

C. Stability of proposed MRAC

The stability of proposed MRAC is defined on the basis of popv's hyper stability theorem. In general the proposed MRAC is represented by an equivalent non-linear feedback system which comprises a feed forward time-invariant linear subsystem and a feedback non-linear time-varying subsystem. It is as shown in fig 4(a). Such a system is said to be globally stable if the following two conditions hold.

1)The transfer function of the feed forward linear time invariant block must be strictly positive real.

2) The nonlinear time-varying block satisfies the Popov's integral inequality

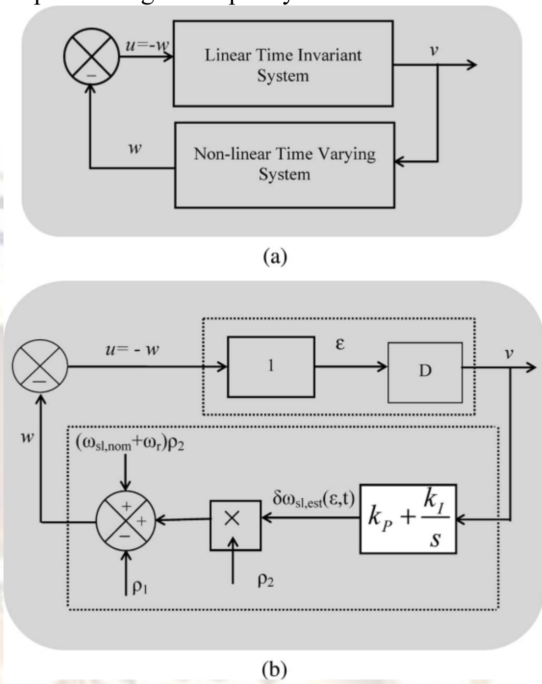


Fig. 4. (a) Nonlinear feedback system, (b) Equivalent structure of the propose scheme.

$$\eta(0.t1) = \int_0^{t_1} v^T \omega dt \geq -\gamma^2 \; \forall t_1 > 0 \quad (7)$$

Where v is input vector, ω is output vector of feedback block, and γ^2 is finite positive constant.

For stability analysis of modified MRAC, fig 2 resolved to Fig 4(b), which the form of Fig 4(a). In Fig 4(b) $\omega = -\rho_1 + \{\omega_{sl\,nom} + \delta\omega_{sl\,est}(\epsilon, t) + \omega_r\}\rho_2$. Here $\rho_1 = v_{qs} i_{ds} - v_{ds} i_{qs}$ and $\rho_2 = \sigma L_s(i_{ds}^2 + i_{qs}^2) + \left(\frac{L_m^2}{L_r}\right) i_{ds}^2$. The details of formation of equivalent model are available in appendix.

Substituting ω in (7) , the inequality becomes

$$\int_0^{t_1}\left\{-v\rho_1 + \omega_{sl} v\rho_2 + \left(k_p + \frac{k_I}{s}\right)v^2\rho_2 + \omega_r v\rho_2\right\}dt \geq -\gamma^2 \quad (8)$$

Using the following well-known inequality, it can be shown that the inequality (8) is satisfied:

$$\int_0^{t1}\frac{d}{dt}\left(f(t) k_1 f(t) dt \geq \frac{-1}{2} k_1 f(0)^2\right) \quad (9)$$

Therefore, a PI controller is sufficient to satisfy Popov's integral inequality. The other criterion for globally stable MRAC is to make the feed forward path gain real positive. To do this an error manipulation block "D" is incorporated in Fig. 2, which achieves the same by properly setting the sign of *ε*. These satisfy both the Popov's criterion and confirm the stability of the system. **D. Sensitivity analysis:**

In order to observe the robustness of proposed system a sensitivity function is designed with respect to parameters of a machine.

a. Sensitivity to Rotor Resistance

The IM model in state space with respect to synchronously rotating reference frame (ω_e) can be expressed as

$$\frac{d}{dt}\begin{bmatrix} i_s \\ \varphi_r \end{bmatrix} = \begin{bmatrix} -(a_1 I + \omega_e J) & a_2 I - a_3 \omega_r J \\ a_4 I & -(a_5 I + \omega_{sl} J) \end{bmatrix} \begin{bmatrix} i_s \\ \varphi_r \end{bmatrix} + \begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} v_s \qquad (10)$$

$$i_s = \begin{bmatrix} I & 0 \end{bmatrix} \begin{bmatrix} i_s \\ \varphi_r \end{bmatrix} \qquad (11)$$

Where

$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$, $a_1 = \left(\frac{1}{\sigma l_s}\right)\left(R_s + \left(\frac{L_m^2}{L_r T_r}\right)\right)$, $a_2 = \left(\frac{1}{\sigma l_s}\right)\left(\frac{L_m}{L_r T_r}\right)$, $a_3 = \left(\frac{1}{\sigma l_s}\right)\left(\frac{L_m}{T_r}\right)$, $a_4 = \frac{L_m}{T_r}$

$a_5 = \frac{1}{T_r}$; Equation 10 can be written as

$\dot{x} = Ax + Bu$

After linearizing with respect to the operating point (x), the small signal model of (11) becomes

$$\Delta\dot{x} = A\Delta x + \Delta A x \qquad (12)$$

$$\Delta i_s = C\Delta x; \qquad (13)$$

Therefore

$$\Delta i_s(s) = c[sI - A]^{-1}\Delta A(s)x. \qquad (14)$$

Where

$$\Delta A = \begin{bmatrix} a_6 I & -a_7 I \\ -a_8 I & a_9 I \end{bmatrix} \Delta R_r$$

Here $a_6 = \left(\frac{1}{\sigma l_s}\right)\left(\frac{L_m^2}{L_r^2}\right)$, $a_7 = \left(\frac{1}{\sigma l_s}\right)\left(\frac{L_m}{L_r^2}\right)$, $a_8 = \frac{L_m}{L_r}$,

$a_9 = \frac{1}{l_r}$

The expression of ($\Delta is/\Delta R$r) can be obtained from (13) using (14). Now, the sensitivity function to rotor resistance variation for the modified MRAC can be expressed as

$$\frac{\Delta\omega_{sl}}{\Delta R_r} = \frac{(V_{qs} - 2K_1\omega_e i_{ds})\frac{\Delta i_{ds}}{\Delta R_r} - (V_{ds} + 2\sigma L_s \omega_e i_{qs})\frac{\Delta i_{qs}}{\Delta R_r}}{(K_1 i_{ds}^2 + \sigma L_s i_{qs}^2) + (K_p + \frac{K_1}{s})^{-1}}$$

(15)

Where $k_1 = \sigma L_s + \frac{L_m^2}{L_r}$ and kP, kI are the PI-controller gains of the adaptation mechanism. The above equation is obtained from (A3) after linearizing with respect to the operating point. The step response of the sensitivity function expressed in (15) is shown in Fig. 6. The response depicts that the MRAC identifies any change in rotor resistance by properly estimating slip speed.

b.Sensitivity to stator resistance

For a small change in Rs, the matrix ΔA can be written as $\Delta A = \begin{bmatrix} \frac{1}{\sigma L_s} I & 0 \\ 0 & 0 \end{bmatrix}$: In the same way as described for rotor resistance, the sensitivity function ($\Delta\omega$sl/ΔRs) for stator resistance can also be derived. The step response of the sensitivity function is given in Fig. 6, which shows that any change in stator resistance does not influence the estimation mechanism in steady state.

E. Sensor less Speed estimation by using MRAC:

Ongoing research has concentrated on the elimination of speed sensor at the machine shaft without deteriorating the dynamic performance of drive control system. Speed estimation is an issue of particular interest with induction motor drives where the mechanical speed of rotor is different from the speed of revolving magnetic field. The advantages of speed sensor less induction motor drives are reduced hardware complexity and lower cost, reduced size of the drive machine, elimination of sensor cable, better noise immunity, increased reliability and less maintenance requirements.

A variety of solutions of ac drives have been proposed in the past few years. In this paper a model based approach is discussed for the speed estimation in induction motor drive utilizing reactive power concept. For the proposed system along with rotor time constant estimation speed can also be estimated. For this purpose additionally flux tuning controllers (which are PI controllers) are used for proper flux orientation. The stability of complete system is achieved by Popov's hyper stability theory as in case of rotor time constant estimation discussed in above sections.

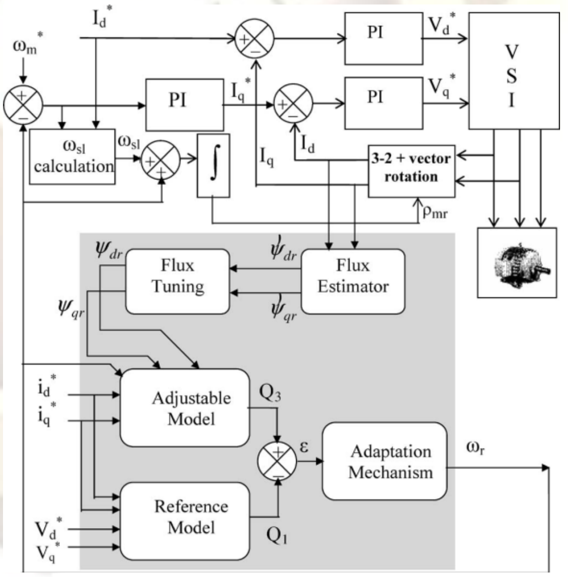


Fig. 5. Vector Controlled IM drive with MRAC-based speed estimator

The block diagram representation of vector controlled IM drive with MRAC based speed estimator is shown in above figure. Here flux estimators are added which can calculate flux from motor currents and these flux linkages are used in instantaneous reactive power i.e. in adjustable model. The error signal obtained from the difference of steady state and instantaneous reactive power is given to adaptation mechanism. The output of adaptation mechanism gives the estimated speed. This can be checked by performing simulation in MATLAB/SIMULINK environment

III. SIMULATION RESULTS

To verify the effectiveness of the proposed rotor time constant estimation algorithm, an IFO-controlled IM drive has been simulated using MATLAB/SIMULINK. The parameters and the rating of the motor are available in Table I.

In Fig. 7, the performance of the drive is tested for step change in rotor time constant. Of course, in a real drive, the rotor resistance never undergoes abrupt variations in response to temperature change due to the large thermal time constant. The step variation represents an extreme case and is used here to show the robustness of the proposed MRAC. Fig. 7(a) represents the actual and estimated rotor time constant and Fig. 7(b) reflects the corresponding flux orientation.

The rotor time constant estimation at sustained zero speed is verified through simulation and the results are presented in Fig. 8. In Fig. 8(a), stator resistance is made double at 6 s. It is observed that change in stator resistance has negligible effect on rotor time constant (Tr) estimation. Fig. 8(b) shows the flux orientation at this speed. In an actual system, rotor resistance varies very slowly with time. Therefore, to observe the variation, data should be captured for long time range, which is not feasible. To overcome this problem, a wrong value of rotor time constant, say *T*ras [Fig. 9(d)], is fed to the ωsl,nom calculation block (of Fig. 2) instead of *R*r,nom. However, the MRAC identifies this mismatch and adjusts itself to return the actual value of rotor time constant, as shown in Fig. 9(c). The corresponding *d*- and *q*-axes rotor fluxes are shown in Fig. 9(a) and (b), respectively.

TABLE I
IM PARAMETERS

Stator phase voltage (V)	200	Rotor leakage inductance	4.342
Shaft power (kW)	2.2	Stator resistance (Ω)	0.877
Pole pairs	2	Rotor resistance (Ω)	1.47
Base speed (rpm)	1430	Rotor inertia (Kg-m^2)	0.015
Magnetizing inductance (mH)	160.8	Rotor friction co-efficient	0.0014
Stator leakage inductance (mH)	4.342		

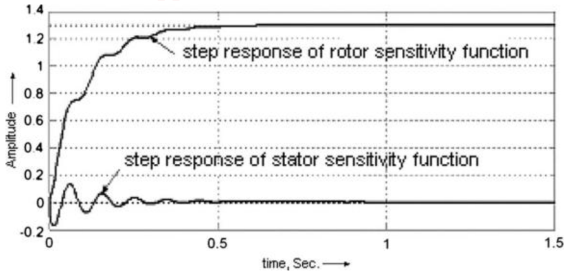
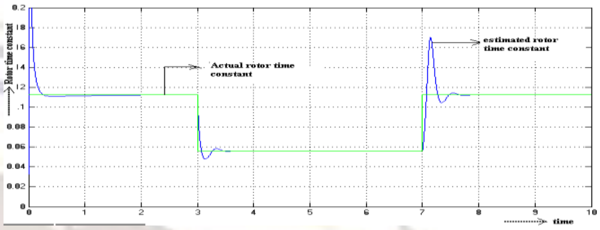
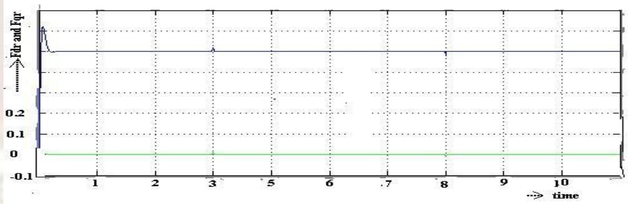


Fig 6 Step response of Stator and rotor sensitivity function

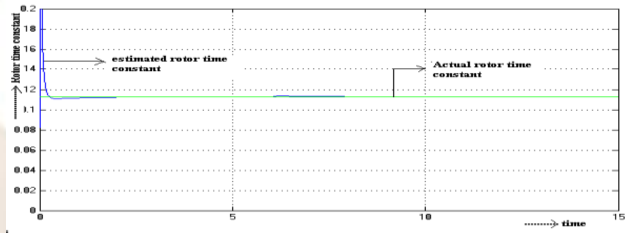


(a)

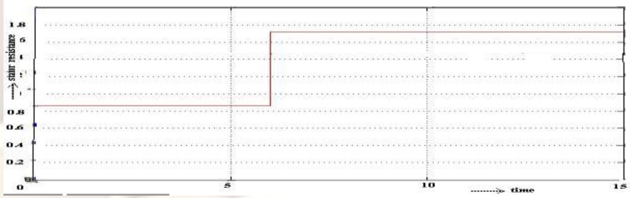


(b)

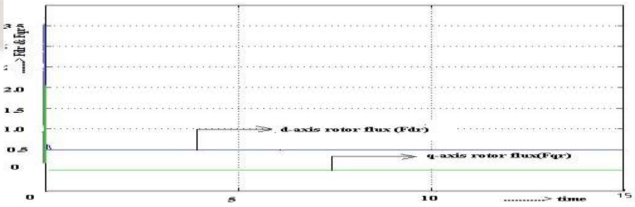
Fig. 7. Step change in rotor time constant: (a) actual and estimated rotor time constant, (b) *d*- and *q*-axis flux.



(a)

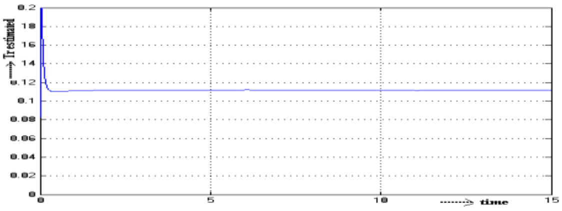


(b)

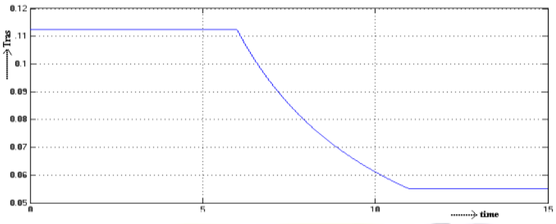


(c)

Fig 8 Step change in stator resistance (a) actual and estimated rotor time constant (b) step change in stator resistance (c) Fdr & Fqr



(a)



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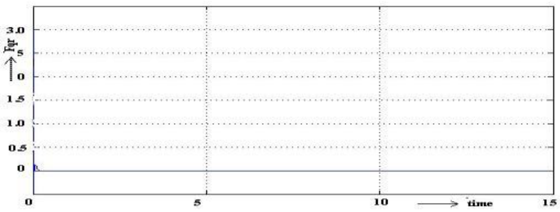
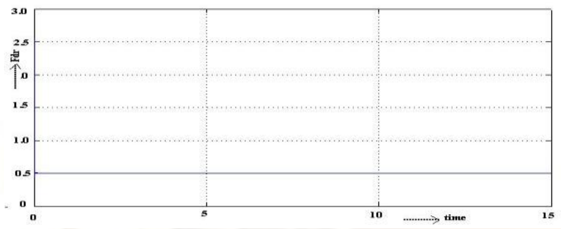


(c)

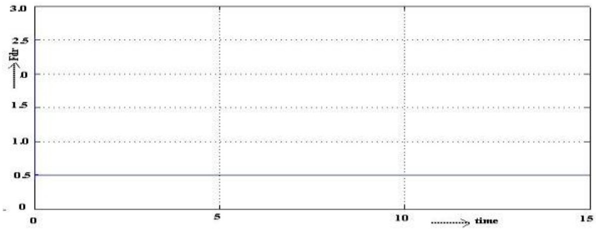


(d)

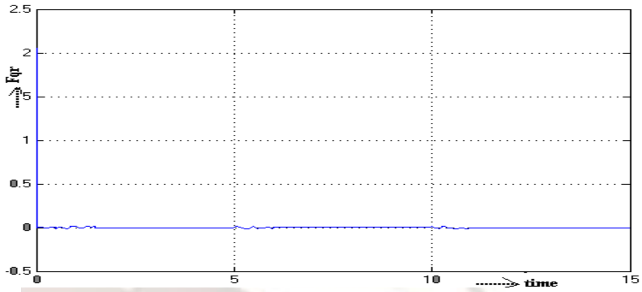
Fig 9.Simulation results for slow variation in rotor time constant: (a)Estimated rotor time constant (b) assumed rotor time constant (c) q-axis rotor flux (d) d-axis rotor flux

IV SIMULATION RESULTS FOR SPEED ESTIMATION BY USING MRAC

The speed estimation algorithm using the proposed reactive power-based MRAC is tested with the step change in command speed. The command speed is set to 100 rad/s at 0.5 s and the same reference is maintained up to 5 s. At 5 s, a negative speed command of −100 rad/s is applied. Finally, the command speed is set to 100 rad/s again at 10 s. The simulation results are reported in Fig. 10, where the figures are seen in the normal order, from top to bottom, the flux of *d*- and *q*-axis, the real rotor speed and the estimated speed. The real rotor speed is illustrated only for monitoring, but not for the control. It can be seen that the system can work steadily with the forward and reverse rotation.



(a)



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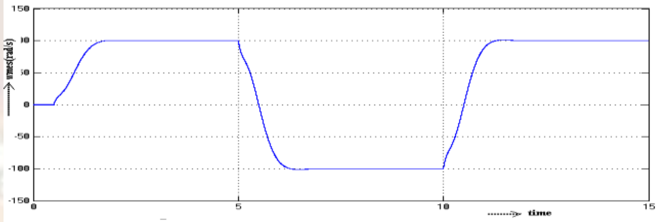
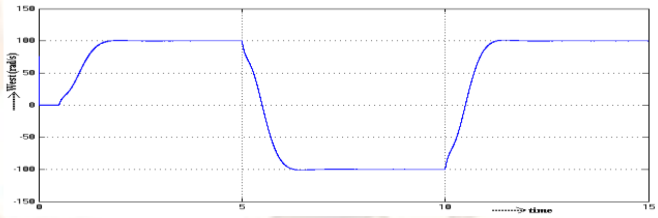


(c)



(d)

Fig. 10. Simulation results for speed reversal: (a) *d*-axis rotor flux, (b) *q*-axis rotor flux, (c) rotor speed (*W*mes), and (d) estimated rotor speed (*W*est).

V. CONCLUSIONS

The detailed performance of MRAC – based rotor resistance and speed estimation techniques are presented in this paper .Instantaneous reactive power is used for reference model and steady state reactive power used in adjustable model. The unique choice has following advantages

1) No flux computation is required and hence free from integrator-related problems.
2) Independent of stator resistance.
3) Both the models in MRAC are free from derivative terms and hence immune to noise.
4) Reference model is absolutely free from machine Parameters
5) Requirement of less computation as the simple expressions are used in both the reference and adjustable models.

In order to obtain rotor time constant estimation in sensor less environment, flux estimators are addedSS to the proposed scheme and speed is estimated. The proposed system is simulated in MATLAB/SIMULINK environment to study the effectiveness of proposed system.

APPENDIX

Formation of the equivalent MRAC as presented in Fig. 4(b) Reference model

$$Q_{ref} = V_{qs} i_{ds} - V_{ds} i_{qs}$$

Adjustable model

$$Q_{est} = \sigma L_s \omega_e [i_{ds}^2 + i_{qs}^2] + \omega_e \frac{L_m^2}{L_r} i_{ds}^2$$

Subtracting (A2) from (A1)

$$Q_{ref} - Q_{est} = (V_{qs} i_{ds} - V_{ds} i_{qs}) - \omega_e(\epsilon, t)[\sigma L_s [i_{ds}^2 + i_{qs}^2] + \frac{L_m^2}{L_r} i_{ds}^2]$$

According to the scheme,

$$\omega_e(\epsilon, t) = \omega_{slnom} + \delta\omega_{slest}(\epsilon, t) + \omega_r$$

There fore

$$\epsilon = \rho_1 - \{\omega_{slnom} + \delta\omega_{slest}(\epsilon, t) + \omega_r\}\rho_2$$

Where

$$\rho_1 = V_{qs} i_{ds} - V_{ds} i_{qs}$$

and

$$\rho_2 = \sigma L_s [i_{ds}^2 + i_{qs}^2] + \frac{L_m^2}{L_r} i_{ds}^2$$

Now $\delta\omega_{slest}(\epsilon, t)$ according to general structure of adaptation law, will be given by expression having the form

$$\delta\omega_{sl}(\square, t) = \left(k_p + \frac{k_i}{s}\right) v$$

where v is the output of block D which will process generalized error as

$$v = D\epsilon$$

Let

$$u = \rho_1 - \{\omega_{slnom} + \delta\omega_{slest}(\epsilon, t) + \omega_r\}\rho_2$$

There fore, from (A3) $\epsilon = u$, again it is assumed that

$$\omega = -u = -\rho_1 + \{\omega_{slnom} + \delta\omega_{slest}(\epsilon, t) + \omega_r\}\rho_2$$

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