

MODEL REFERENCE ADAPTIVE CONTROL FOR IFO-CONTROLLED AC DRIVES FOR MOTORS AND GENERATORS

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Abstract— This article investigates a modified indirect field oriented control strategy that employs an adaptive scheme for rotor time constant. The adaptive strategy uses a reference model that only depends on stator voltages and currents of machine. The application of the proposed scheme allows improving performance and stability of Indirect Field Oriented Control (IFOC) in AC drives, both in motoring or generating operation. Simulation results are presented in order to demonstrate the feasibility of the proposed methodology.

Keywords— AC Drives, IFOC, MRAC, Electric Machines.

Resumo— Este trabalho apresenta um controle orientado pelo campo modificado, que emprega uma malha de adaptação da constante rotórica. A estratégia adaptativa utiliza um modelo de referência dependente apenas das tensões e corrente do estator da máquina. A aplicação do esquema proposto permite aprimorar o desempenho e estabilidade de acionamentos baseados em controle indireto orientado pelo campo (Indirect Field Oriented Control, IFOC), tanto na operação como motor ou como gerador. Resultados de simulação são apresentados a fim de demonstrar a viabilidade da presente metodologia.

Palavras-chave— Acionamento de Máquinas, IFOC, MRAC, Máquinas Elétricas.

1 Introduction

High performance speed controls for induction electric machines generally employ field oriented control (Lorenz et al., 1994). In this strategy, there are two approaches: direct and indirect control. The direct control uses feedback for flux control, which usually requires estimation, once sensing is infeasible in most cases. The estimation however is not trivial, because ac machines are nonlinear time varying systems. The indirect control, in other hand, uses a feedforward approach for flux control. Due to ease of implementation indirect field oriented control (IFOC) is preferable to the direct approach in most industrial application (Lorenz et al., 1994).

The indirect control, however, have critical problems related with parameter sensitivity. In particular the changes in rotor time constant are important, since these violate the flux-torque decoupling condition (Lorenz and Lawson, 1988; Mastorocostas et al., 2006). The rotor time constant usual changes with the temperature, and control with fixed parameters are not compatible with some systems, mainly high performance applications (de Souza Ribeiro et al., 1997; Marino et al., 2008). To overcome this limitation, several techniques were proposed in literature for on-line estimation of parameters (Wang et al., 2007; Jevremovic et al., 2010; Kamankesh and Khaburi, 2009) and model reference adaptive system (de Souza Ribeiro et al., 1997; Marino et al., 2008; Larabi and Boucherit, 2010).

Simple reference models for adaptation in IFOC were presented in (Rowan et al., 1989). The

presented models are free from rotor time constant, and use only voltage and currents from IFOC scheme. Using one of those a model reference adaptive controller (MRAC) was presented in a torque controlled speed sensorless approach (Jacobina et al., 2000). Similar schemes are employed for the same purpose in (De Azevedo et al., 2002; Vitorino et al., 2011).

This paper presents four MRAC systems derived by Lyapunov's methods using the models of (Rowan et al., 1989). Since the adaptive laws should ensure stability, modifications to the previous MRAC from literature are proposed. The present strategy allows operation both as motor or generator, adapting the rotor time constant in the standard IFOC scheme. To validate the present MRAC systems, a simulation is presented.

2 Development

This section presents the derivation of adaptive laws for MRAC IFOC induction machines. The first subsection presents the machine model and the principles of IFOC control. The second subsection present the reference models employed, and the third subsection, the development of adaptive laws.

2.1 Indirect Field Control

A symmetric three-phase induction machine saturation free can be represented by a vector model in a generic reference frame, indicated by superscript g , from (1) to (6) (Jacobina et al., 2000). The equations (1) to (4) represent the electric model,

whereas (5) to (6), the mechanic model.

$$\mathbf{v}_s^g = r_s \mathbf{i}_s^g + \frac{d\phi_s^g}{dt} + j\omega_g \phi_s^g \quad (1)$$

$$0 = r_r \mathbf{i}_r^g + \frac{d\phi_r^g}{dt} + j(\omega_g - \omega_r) \phi_r^g \quad (2)$$

$$\phi_s^g = l_s \mathbf{i}_s^g + l_m \mathbf{i}_r^g \quad (3)$$

$$\phi_r^g = l_r \mathbf{i}_r^g + l_m \mathbf{i}_s^g \quad (4)$$

$$P(T_e - T_m) = \frac{Jd\omega_r}{dt} + F\omega_r \quad (5)$$

$$T_e = P|i_s|sen(\delta_i - \delta_a) = P\frac{lm}{lr}|i_s||\phi_r|sen(\delta_i - \delta_a) \quad (6)$$

Vector $v = v_d + jv_q$ and $i = i_d + ji_q$ are the current and voltage in the reference frame, r_r e r_s , l_s , l_r , l_m , are the parameters of resistance and inductance, from stator, rotor, and mutual, $\phi = \phi_d + j\phi_q$ is the magnetic flux vector, P is the pole pair number, T is the torque, the subscript e and m , is the mechanic and electric torque, the subscript r and s define stator and rotor parameters. The parameters J and F are the inertia and friction coefficients associated with the rotor and mechanical coupling of the machine. The equivalent circuit for the adopted electrical model is shown in Fig. 1, where $l_{ls} = l_s - l_m$ and $l_{lr} = l_r - l_m$.

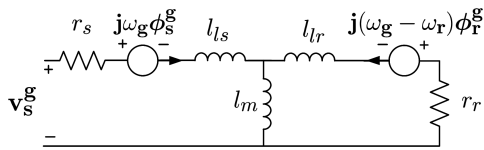


Figure 1: Arbitrary reference-frame equivalent circuits for a 3-phase, symmetrical induction machine.

The standard indirect field oriented control employs the rotor flux reference frame. The dynamic model, obtained from (3) and (4), is given by

$$\frac{l_m}{\tau_r} i_{sd}^e = \frac{1}{\tau_r} |\phi_r| + \frac{d}{dt} |\phi_r| \quad (7)$$

$$\omega_{sl} = \frac{1}{\tau_r} \frac{i_{sq}^e}{i_{sd}^e} \quad (8)$$

, where the superscript e indicates the rotor flux reference frame, τ_r is the rotor time constant ($\tau_r = l_r/r_r$) and ω_{sl} is the slip of the induction machine. The electric torque is expressed by

$$T_e = Pl_m \frac{i_{sq}^e |\phi_r|}{l_r} \quad (9)$$

In the adopted reference frame, the torque and flux control can be decoupled. Considering a constant flux, the torque is controlled by i_{sq}^e .

The feedforward gain of flux control can be obtained from (7). The reference currents are then given by

$$i_{sd}^{e*} = \frac{1}{l_m} |\phi_r|^* \quad (10)$$

$$i_{sq}^{e*} = \frac{l_r}{Pl_m^2} \frac{T_e^*}{i_{sd}^{e*}} \quad (11)$$

Since voltage source inverters are usually employed, a current tracking loop is necessary. For this proportional integrative compensators with feedback are employed. In the standard scheme, the transformation from rotor flux reference e to stationary reference s requires the rotor flux angle θ_e . This can be obtained from (8) and the measured rotor angular speed, and is given by

$$\theta_e = \int_0^t \omega_{sl}(\tau) d\tau + \int_0^t \omega_r(\tau) d\tau \quad (12)$$

The outputs of the PI compensators are the voltages to be applied in the synchronous reference frame. The stationary references are then given by

$$v_{sd}^{s*} = v_{sd}^{e*} \cos(\theta_e) - v_{sq}^{e*} \sin(\theta_e) \quad (13)$$

$$v_{sq}^{s*} = v_{sd}^{e*} \sin(\theta_e) + v_{sq}^{e*} \cos(\theta_e) \quad (14)$$

Since ω_{sl} is inversely proportional to τ_r , the control is very sensitive to this constant. For a speed controlled IFOC on motoring operation, the convergence of control only occurs if the torque reaches the necessary value to overcome the load torque and friction in the reference speed. According to (8) if τ_r changes, so the relation i_{sq}^e/i_{sd}^e changes, implying that the control will converge to a rotor flux which differs from reference. This operation can even become unstable. If the flux becomes too low, i_{sq}^e , according to (9), needs to become too high to reach the necessary electric torque, beyond limits of the implementation. For those reasons, besides performance and stability, variations of the rotor time constant on IFOC machines also results in problems related with efficiency and durability of the equipment.

The proposed MRAC IFCO system is presented in Fig. 2. This can be seen as an extension of the standard IFOC, where the reference model are used for a adaptive scheme of the τ_r parameter. The adaptive mechanism uses IFOC internal loop variables. It does not demand any extra measurement, and does not inject any extra signal for estimation. The reference models and the adaptation mechanism are discussed in the following sections.

2.2 Reference Models

Reference models based on stator variables have been employed for development of MRAC (de Souza Ribeiro et al., 1997). One of the main aspects in the MRAC project is to guarantee an

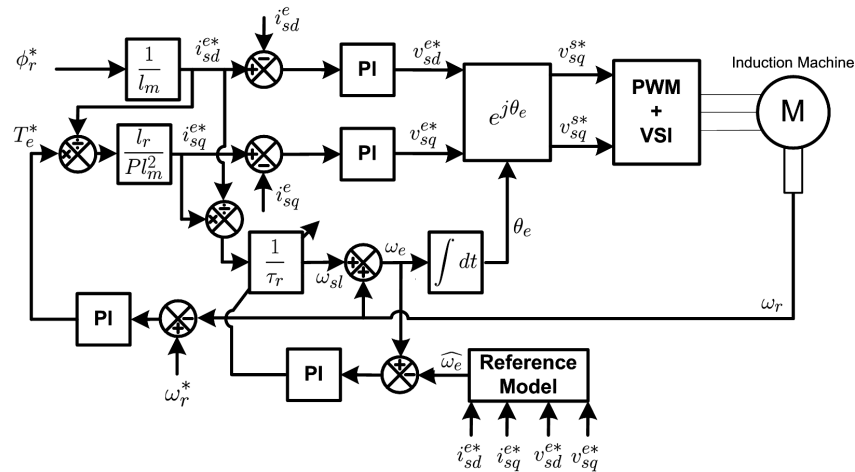


Figure 2: Block diagram of the MRAC IFOC scheme.

adjustment mechanism so that a stable system is obtained, and the error converges to zero. On this paper four references models are studied. The models are used to estimation of ω_e , independent of rotor resistance, and thus avoiding the sensitive problems related with the rotor time constant. All models are obtained by using steady-state IFOC conditions.

The first reference model uses the d-axis voltage equation and it is given by

$$\omega_e = \frac{r_s i_{sd}^{e*} - v_{sd}^{e*}}{\sigma l_s i_{sq}^{e*}} \quad (15)$$

, where $\sigma = 1 - l_m^2 / (l_s l_r)$. The stator voltage v_{sd}^{e*} is obtained from the output of current tracking loop in the synchronous reference frame.

The second reference model uses the q-axis voltage equation and it is given by

$$\omega_e = \frac{-r_s i_{sq}^{e*} + v_{sq}^{e*}}{l_s i_{sd}^{e*}} \quad (16)$$

The stator voltage v_{sq}^{e*} is also obtained from the output of current tracking loop in the synchronous reference frame.

The third reference model is obtained by estimation of reactive power handled by an induction machine, which is given by

$$Q = i_{sq}^{e*} v_{sq}^{e*} - i_{sd}^{e*} v_{sd}^{e*} \quad (17)$$

, and the reference value of Q^* is obtained by

$$Q^* = \omega_e(l_s(i_{sd}^{e*})^2 + \sigma l_s i_{sq}^{e*}) \quad (18)$$

The reference model of reactive power is given by

$$\omega_e = \frac{i_{sq}^{e*} v_{sq}^{e*} - i_{sd}^{e*} v_{sd}^{e*}}{l_s (i_{sd}^{e*})^2 + \sigma l_s i_{sq}^{e*}} \quad (19)$$

Similar to the previous model, the active power can be used. The actual active power is given by

$$P = i_{sq}^{e*} v_{sq}^{e*} + i_{sd}^{e*} v_{sd}^{e*} \quad (20)$$

, while the reference active power is given by

$$P = \omega_e(l_s - \sigma l_s)i_{sd}^*i_{sq}^* + r_s((i_{sq}^*)^2 + (i_{sd}^*)^2) \quad (21)$$

The fourth reference model is given by

$$\omega_e = \frac{i_{sq}^{e*} v_{sq}^{e*} + i_{sd}^{e*} v_{sd}^{e*} + r_s((i_{sq}^{e*})^2 + (i_{sd}^{e*})^2)}{(l_s - \sigma l_s) i_{sd}^{e*} i_{sq}^{e*}} \quad (22)$$

2.3 Model Reference Adaptive Control

Lyapunov's theory can be used to construct the adaptive laws for the MRAC system. For this, the error for the system with the previous reference models is defined by

$$e(t) = \omega_e(t) - \widehat{\omega}_e(t) \quad (23)$$

, where $\omega_e(t) = \omega_{sl} + \omega_r$, using (8) and the measured rotor speed, and $\widehat{\omega}_e(t)$ is obtained by the reference models (15), (16), (19) or (22). The adaptive mechanism should be slower than IFOC to avoid interactions between loops. Considering stationary operation of IFOC, the derivative of is defined error as

$$\frac{de(t)}{dt} = \frac{dK_x(t)}{dt} K_1 \quad (24)$$

, where

$$K_1 = \frac{1}{\tau_r} \frac{i_{sq}^e}{i_{sd}^e}$$

, and $K_x(t)$ is a direct proportional gain for tuning τ_r . For purpose of application of Lyapunov's second method, an energy function $V(t)$ is defined as

$$V(t) = e(t)^2/2 \quad (25)$$

, which is Lyapunov's quadratic function. Since (25) is positive definite, for a stable system the derivative $dV(t)/dt$ must be negative definite. The derivative of (25) is

$$\frac{dV(t)}{dt} = e(t) \frac{de(t)}{dt} \quad (26)$$

Table 1: Three-phase induction machine parameters.

r_s	1Ω
r_r	1Ω
l_s	$0.205 H$
l_r	$0.205 H$
l_m	$0.2 H$
P	2
J	$0.01 kg.m^2$
F	$0.04 N.m.s$

The following rule of adaptation is defined

$$\frac{dK_x(t)}{dt} = K_{ai}e(t) + K_{ap}\frac{de(t)}{dt} \quad (27)$$

Using (27) and (24) on (26), it is obtained

$$\frac{dV}{dt} = e(t)^2 K_1 \left(\frac{K_{ai}}{1 - K_{ap}K_1} \right) \quad (28)$$

As long as $K_1 > 0$ (motoring), and $K_{ai}/(1 - K_{ap}K_1) > 0$, (25) is positive definite and (28) is negative definite, so the error converges to zero. If $K_1 < 0$ (generating), so $K_{ai}/(1 - K_{ap}K_1) < 0$ need to be hold. That analysis shows the need for definition on motoring or generating region. From the operation mode is then defined the appropriate signal of K_{ai} and K_{ap} . A safe choice is $k_{ai} > 0$ and $k_{ap} > 0$, such as $K_{ai} = k_{ai}$ and $K_{ap} = k_{ai}$ for motoring, and $K_{ai} = -k_{ai}$ and $K_{ap} = -k_{ai}$ for generating.

3 Simulation Results

A simulation is performed in order to validate the present MRAC IFOC systems. The numerical implementation is made using Matlab©, with a machine using the parameters of Table I, which are according to the description of (1) to (6). The performance of the improved MRAC IFOC is referred to the standard IFOC, in motoring and generating operation mode.

In the simulation a scenario is developed with load torque transients and a transition from motoring to generating. The scenario starts with the machine stopped, for convergence of the flux controllers. The reference value of rotor flux is 0.5 Wb. At 3 seconds, the speed controller is activated and set with a reference of 150 rad/s. Still, a load torque of 3 N.m is applied. At instant of 8 and 10 seconds a transient of load torque is realized, to 6 N.m and 3 N.m, respectively. At instant of 12 seconds, the machine starts the generating operation, with change of load torque direction and magnitude.

In Fig. 3 is presented the results of rotor speed, electric torque and load torque. Fig. 4 presents the rotor flux components dq in the synchronous reference frame. Fig. 5 presents the

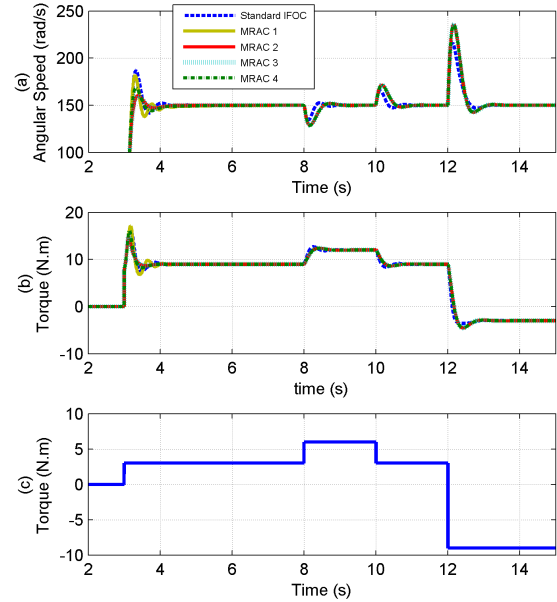


Figure 3: Operation of standard IFOC and proposed MRAC IFOC systems. (a) Rotor Speed. (b) Electric Torque. (c) Load Torque.

estimated flux rotor speed $\widehat{\omega}_e(t)$ and $\omega_e(t)$ obtained with the measured ω_r and relation (12). In the initialization the rotor time constant was mismatched with 50%.

At the beginning of the simulation, as the reference frame is stopped, there is no error with the reference systems, and so there is no adaptation. When the speed controller is activated at 3 seconds it converges to the reference value. As the reference frame starts moving, the adaptive system start the tuning process of τ_r .

While the standard IFOC presents a large error with the rotor magnetic flux reference on the whole operation, the MRAC systems start the adaptation process when the machine starts to accelerate. The MRAC reduces the error (23) to zero, allowing the correct estimation of $\omega_e(t)$. On the transients at 8 and 10 seconds, as the adaptive scheme have already converged, this scheme is not affected and the rotor flux keeps close to the reference of 0.5 Wb. In the generating operation, while the standard IFOC keeps large error with the magnetic rotor flux reference, the MRAC systems keeps correctly tuned in a stable way.

4 CONCLUSION

This paper has demonstrated a feasible use of MRAC in IFOC AC drives for machines in motoring and generating operation. The developed adaptive laws aims to keep the IFOC permanently tuned with respect of time rotor constant, as well as ensures a stable dynamics. Simulation results have been presented to validate the methodology, and stationary and transitory analysis have been

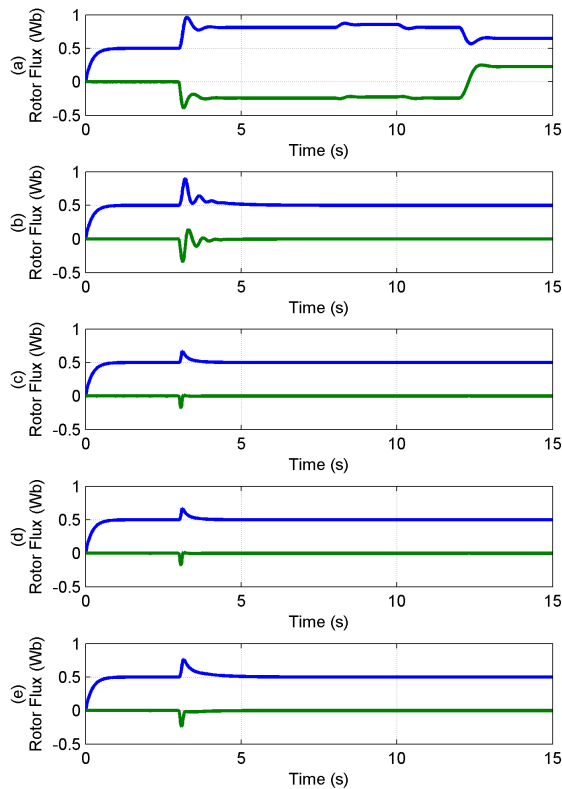


Figure 4: Rotor flux in the synchronous reference frame. (a) standard IFOC. (b) MRAC IFOC with q-axis model. (c) MRAC IFOC d-axis model. (d) MRAC IFOC with reactive power model. (e) MRAC IFOC with active power model.

performed.

The present technique is simple and provides a high performance speed control solution. The scheme do not relying on any signal injection technique, but is based in the standard IFOC, and can even be implemented as an extension on systems already in operation. This scheme can be used where there are performance constraints, or to improve stability and efficiency where the machine operates in a wide speed or load torque range.

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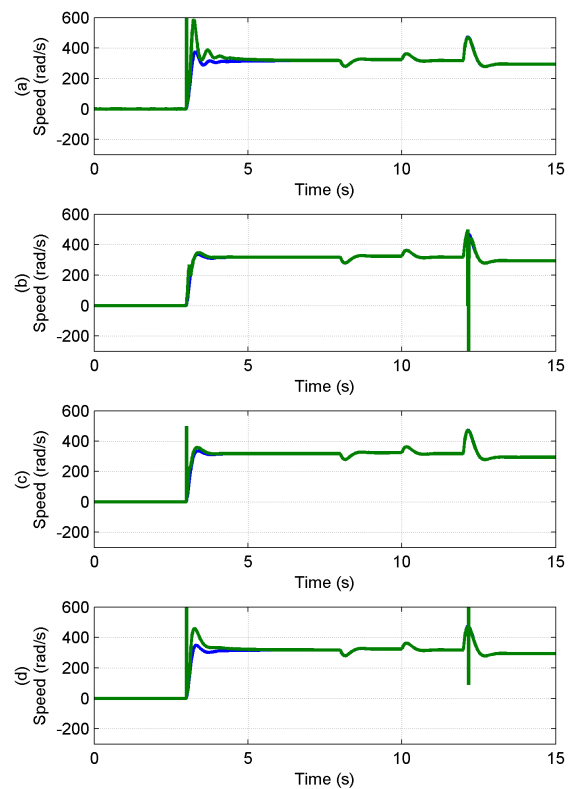


Figure 5: Estimated and measured rotor flux speed. (a) MRAC IFOC with q-axis model. (b) MRAC IFOC d-axis model. (c) MRAC IFOC with reactive power model. (d) MRAC IFOC with active power model. Green is the reference systems and blue is the calculated with the rotor speed.

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