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A New Approach for Flux and Rotor Resistance Estimation of Induction Motors ⋆

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Abstract: In this paper we address the problems of flux and rotor resistance estimation of induction motors. We propose a radically new approach that combines the recently introduced techniques of parameter estimation based observers (PEBO) with the dynamic regression extension and mixing (DREM) parameter adaptation. The PEBO framework is used to recast the flux observation task as a parameter estimation problem, for which the DREM technique is utilised. The resulting flux observer is then combined with a standard gradient estimator for the rotor resistance. Simulation results of an adaptive implementation of the classical field oriented controller demonstrate the effectiveness of the proposed flux observer and rotor resistance estimator even in closed-loop operation.

Keywords: Adaptive observer, nonlinear regressor, induction motor.

1. INTRODUCTION

Induction motors (IM) have traditionally been the workhorse of industry in a wide range of servo applications. Since the dynamics of the IM is highly nonlinear and its state is not available for measurement it has been necessary to develop advanced control techniques when high performance requirements are imposed. In 1972 Blaschke and Hasse introduced the so-called field-oriented control (FOC) method, which is based on a nonlinear coordinate change that makes the dynamics of the IM very similar to the equations of a DC motor. Since the control of DC motors is much simpler and better understood, FOC has become the *de facto* industry standard. A drawback of FOC is that it requires knowledge of the rotor resistance, which varies significantly with temperature, frequency and current amplitude. Even though it has been shown in (de Wit et al. (1996)) that stability is preserved for very large errors in rotor resistance estimation, this mismatch seriously affects the performance: it degrades the flux regulation, which may lead to saturation or underexcitation, slows–down the torque response and induces a steady-state error.

In view of the situation above it is widely recognized that one of the most practically relevant open problems in IM control is the development of high-performance schemes that are insensitive to rotor resistance variations, *e.g.*, incorporating adaptation features. A globally stable adaptive design for current-fed IMs with unknown rotor resistance and load torque was reported in Marino et al. (2000)—however, the proposed controller is much more complicated than the basic FOC and is difficult to implement and tune. See (Ortega et al. (1998) and Peresada et al. (2003)) for some theoretical and experimental evidence.

The problem of estimating the rotor resistance of induction motors is also important in other applications, including fault detection and motor calibration, see (Marino et al. (1995), Pavlov and Zaremba (2001), Castaldi et al. (2005)) and references therein. A well-known approach to estimate the rotor resistance (or rotor time constant that also involves the rotor self-inductance), is to inject a current perturbation signal (Matsuo and Lipo (1985)) or adding short duration pulses, see (Wade et al. (1997)). Other examples in the literature include the use of extended Kalman filters (Laroche et al. (2008)), least-squares methods (Li-Campbell et al. (2007),Wang et al. (2007)) or methods based on the reactive-power reference model Roncero-Sánchez et al. (2007). More recently, other authors proposed estimation techniques based on sliding modes (Proca and Keyhani (2007), Kenné et al. (2010)) or Lyapunov-based methods (Salmasi and Najafabadi (2011), Verrelli et al. (2014)).

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To estimate the rotor resistance we propose in this paper a three step procedure. First, using the novel PEBO reported in (Ortega et al. (2015)) reformulate the problem of flux observation as a parameter estimation problem. Second, use the new, high performance, DREM parameter adaptation technique of (Aranovskiy et al. (2016b)) to estimate these unknown parameters. Finally, to apply some filtering techniques to the stator current equation—similar to the ones used in (Bobtsov et al. (2015))—to derive a linear regression model for the rotor resistance for which a standard gradient estimator is applied. Since the current dynamics depends on the rotor flux, in this last step this quantity is replaced, in a certainty equivalent way, by its observed value generated via the PEBO-DREM combination described above. In the paper we also explore a second possibility to estimate the rotor resistance which is to proceed as before but using the rotor flux equation instead of the stator current equation. Even though it is not proven, simulation results show that proposed flux and resistance observer works in the closed loop system when the estimates are used by FOC.

The use of DREM in the PEBO, instead of a classical gradient, is motivated by the fact that the former exhibits a far better transient performance behaviour, see Aranovskiy et al. (2016a). Moreover, as shown in (Aranovskiy et al. (2016b)), parameter convergence is guaranteed without the usual requirement of regressor persistency of excitation (PE)—imposing, instead, that the regressor should not be square-integrable.

If PE condition is satisfied both DREM-based and classical gradient estimators converge exponentially fast. DREM estimator also ensures global convergence if the regressor is not square-integrable, while the convergence of the gradient one is not guaranteed in this case. Relaxing the PE requirement is a fundamental feature of DREM that plays a central role in this IM application.

The remaining of the paper is organized as follows. In Section 2 we present the model of the IM and the problem formulation. Sections 3 and 4 contain the main results, namely, in the former we present the new flux observer while the latter contains the two rotor resistance estimators. In Section 5 we present simulation results of an adaptive implementation of the classical field oriented controller, which demonstrate the effectiveness of the proposed flux observer and rotor resistance estimator even in closed-loop operation. In the simulations we compare the use of standard gradient estimator and DREM in the proposed PEBO, showing the improved performance of the latter. We also compare in simulations the two rotor resistance observers proposed in the paper. Our work is wrapped-up with concluding remarks in Section 6.

2. IM MODEL AND PROBLEM STATEMENT

The classical two-phase *a*-*b* model of an induction motor is given by (Astolfi et al. (2008))

$$\frac{\sigma L_s L_r}{M}\frac{d}{dt}i_{ab} = -\left(\frac{R_s L_r}{M}+\frac{MR_r}{L_r}\right)i_{ab} + \left(\frac{R_r}{Lr}I - n_p\omega J\right)\lambda_{ab} + \frac{L_r}{M}v_{ab} \qquad (1)$$

$$\dot{\lambda}_{ab} = \frac{MR_r}{L_r}i_{ab} - \left(\frac{R_r}{L_r}I - n_p\omega J\right)\lambda_{ab}, \qquad (2)$$

$$\dot{\omega} = \frac{n_p M}{J_m L_r}i_{ab}^\top J\lambda_{ab} - \frac{\tau_L}{J_m}, \qquad (3)$$

where $i_{ab} \in \mathbb{R}^2$ is the stator current, $v_{ab} \in \mathbb{R}^2$ is the stator voltage, $\lambda_{ab} \in \mathbb{R}^2$ is the rotor flux, ω is the rotor speed, $R_r, L_r, M, n_p, J_m, R_s, L_s$ are positive constants representing the rotor resistance, rotor inductance, mutual inductance, number of pole pairs, moment of inertia, stator resistance and stator inductance, respectively, $\sigma = 1 - M^2/(L_s L_r)$ is the leakage parameter, τ_L is the unknown load torque that, as always, is assumed *constant*,[1] and

$$I = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}, \quad J = \begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix}.$$

The objective is to estimate R_r and λ_{ab}, assuming that all other motor parameters are known and the stator currents and voltages and the rotor speed are measured.

As usual in open-loop observation scenarios, we assume that the external signals v_{ab} and τ_L are such that the system (1)-(3) is forward complete and all the signals are *bounded*. Furthermore, to complete the stability analysis we will assume that v_{ab} and i_{ab} are *absolutely integrable*. This assumption is consistent with the motor operation since, in steady-state, these signals are periodic of zero-mean.

3. ROTOR FLUX OBSERVER

In this section we first derive, from (1), some dynamic relations that are instrumental to formulate the rotor flux observation problem using PEBO, *i.e.*, to be able to reconstruct the flux by estimating from a linear regression some suitable initial conditions. Then, we apply DREM to estimate the parameters of this regression.

3.1 Model reparametrization

Let us define the signal, which appears in (1) and (2),

$$\zeta := \left(\frac{R_r}{L_r}I - n_p\omega J\right)\lambda_{ab}.$$

Replacing ζ from (1) into (2) yields

$$\dot{\lambda}_{ab} = -\frac{\sigma L_s L_r}{M}\frac{d}{dt}i_{ab} - \frac{R_s L_r}{M}i_{ab} + \frac{L_r}{M}v_{ab}. \qquad (4)$$

Integrating the latter we obtain

$$\lambda_{ab}(t) = \lambda_{ab}(0) - \frac{\sigma L_s L_r}{M}i_{ab}(t) + \frac{\sigma L_s L_r}{M}i_{ab}(0) - \frac{R_s L_r}{M}z_2(t) + \frac{R_s L_r}{M}z_2(0) + \frac{L_r}{M}z_1(t) - \frac{L_r}{M}z_1(0), \qquad (5)$$

where we introduced two auxiliary variables

$$\dot{z}_1 = v_{ab}$$
$$\dot{z}_2 = i_{ab}. \qquad (6)$$

Notice that, in view of the absolute integrability assumption of v_{ab} and i_{ab}, the vector z is *bounded*. Then, defining the *unknown* constant vector

$$\eta := \lambda_{ab}(0) + \frac{\sigma L_s L_r}{M}i_{ab}(0) + \frac{R_s L_r}{M}z_2(0) - \frac{L_r}{M}z_1(0)$$

[1] The rationale for this assumption is the time scale separation between the electrical and the mechanical dynamics.