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Induction machine speed control with flux optimization

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ABSTRACT

A new speed control strategy is developed, based on a machine model that accounts for the magnetic characteristic saturation. The control strategy includes a flux reference generator, designed to meet optimal operational conditions, and a speed controller designed using nonlinear techniques. Both flux generation and speed control laws involve the machine state variables. The performances of the proposed control strategy are formally analyzed and its supremacy with respect to standard control solutions is illustrated through simulation.

1. Introduction

It is widely recognized that the induction motor is going to become the main actuator for industrial purposes. Compared to other motors (e.g. DC machine), the induction motor provides a better power/mass ratio, simpler maintenance (no mechanical commutators) and relatively lower cost. However, the induction motor control problem is more complex, due to its multivariable and highly nonlinear nature. Finally, not all machine state variables are accessible to measurement.

Most previous control strategies for induction machine speed regulation are based on standard models obtained under the assumption that the machine magnetic characteristic is static and linear. As a matter of fact, such a characteristic is nonlinear and physical machines exhibit several nonlinear features e.g. flux saturation (Fig. 1). Nevertheless, standard models can still be used in speed control design, provided that the rotor flux regulation is performed around a fixed nominal value. This was generally the case, in previous control strategies, choosing a constant reference flux (Espinosa, Ortega, & Nicklasson, 1997; Kim, Ortega, Charara, & Vilain, 1997; Lubineau, Dion, Dugard, & Roye, 2000; Ortega & Espinosa, 1993; Ortega, Nicklasson, & Espinosa-Perez, 1996; Von Raumer, Dion, Dugard, & Thomas, 1994). In such a situation, the machine efficiency is maximal only when the load torque is close to its nominal value. However, in practical applications, the load torque is usually not a priori fixed and may be subject to wide range variations (Leonard, 2001; Novotnak, Chiasson, & Bodson, 1999). Then, keeping the flux near the nominal value will result in a useless energy stored in stator inductances, reducing the machine efficiency, especially when the load torque is small (compared to nominal load). Inversely, if the flux reference is given a small value, the achievable machine motor torque will not be sufficient to counteract large load torques. Therefore, speed control strategies involving constant flux reference are unable to guarantee optimal machine performances (optimality is generally understood in the sense of efficiency, power factor and maximal torque). To overcome the above shortcomings, it is necessary to develop new speed control strategies involving online tuning of the flux reference to track varying speed reference in presence of load torque changes. When these are important (ranging from 0 to nominal values), the optimal flux reference will in turn undergo wide range variations implying large excursions of the working point on the magnetic characteristic. Therefore, the development of speed control strategies, guaranteeing optimal machine performances, must rely on a machine model that takes into account the nonlinear feature of the magnetic characteristic. Fortunately, an example of such models was recently developed and experimentally validated (Ouadi, Giri, & Dugard, 2004).

In the light of the above discussion, it becomes clear that speed control strategies for induction machines involve two main components: a speed/flux controller and an optimal flux reference generator. As already mentioned, the flux and speed references are generally chosen independently in earlier control strategies. Typically, the flux reference is generally given a (non-optimal) fixed value and the speed regulator is obtained (using various design techniques) from the machine standard model, supposing

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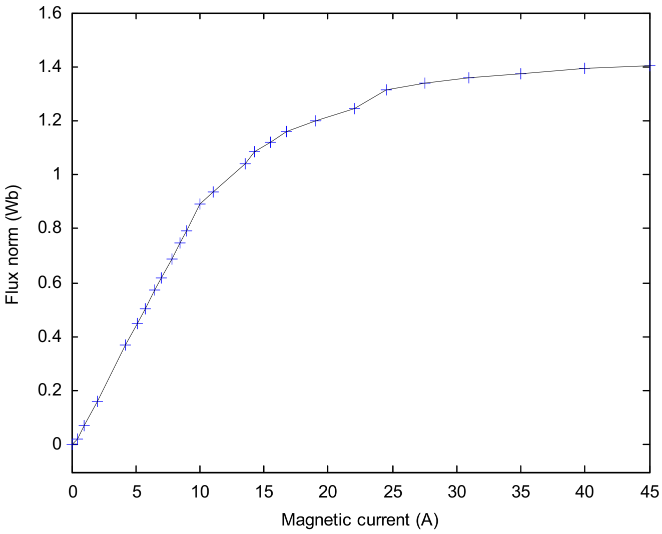

Fig. 1. Magnetic characteristic experimentally obtained in Ouadi et al. (2004) for a 7.5 KW induction motor: rotor flux norm Φ_r (Wb) *versus* magnetic current I_μ (A).

a linear magnetic characteristic (e.g. Espinosa et al., 1997; Kim et al., 1997; Leonard, 2001; Lubineau et al., 2000; Ortega & Espinosa, 1993; Ortega et al., 1996; Von Raumer et al., 1994). A serious attempt to develop control strategies involving flux reference optimization was reported in (Novotnak et al., 1999): based on a field-oriented model accounting for magnetic saturation, a flux reference generator was designed to obtain online the maximum torque. As pointed out by the authors themselves, the saturation effect was accounted for in a '*somewhat ad hoc manner*'. Specifically, a model of the saturated magnetic characteristic was just added to an existing (unsaturated) model of the induction machine (just as suggested in Heinemann & Leonhard, 1990). This differs from the approach developed in (Ouadi et al., 2004) where the magnetic characteristic is accounted for, together with the basic electromagnetic laws, all along the modeling procedure. Furthermore, it is known that field-oriented models, like the one based upon in Novotnak et al. (1999), lead to controllers that are highly sensitive to rotor resistance variations. Finally, it is not formally proved in Novotnak et al. (1999) that the proposed control strategy actually achieves the desired control performances (closed-loop stability, speed and flux reference tracking). An alternative control strategy, refereed to maximum torque per Ampere, consists in obtaining stator current reference generators that maximize the machine torque, see e.g. Kwon & Sudhoff (2005) and Wasynczuk et al. (1998). There, the current generators are designed, based on a standard field-oriented model neglecting the magnetic saturation. It is clear that neglecting the magnetic saturation effect contrasts with the objective of wide range torque variation control. Indeed, such an objective necessitates a wide range variation of the (d-axis) stator current which entails large flux variations.

In the present paper, a new control strategy is developed that involves an optimal flux reference and a speed and flux controller. Both components are designed using the model developed in Ouadi et al. (2004) that accounts for magnetic saturation. The flux reference optimality is to be understood in the sense of stator current minimization. Therefore, the obtained optimal flux reference law involves the machine stator currents which are state variables. The speed/flux controller, designed by the backstepping technique, turns out to be quite different from previous standard control strategies that assume linear magnetic characteristic and involve constant flux references. The new controller is formally proved to be globally asymptotically stable and enforces the speed to perfectly track its varying reference trajectory, despite the changing load torque. It is also checked through simulations that, in presence of load torque variations and rotor resistance uncertainties, the new control strategy is better than previous strategies, from the energetic viewpoint.

Table 1
List of acronyms.

LM-model:	Linear magnetic characteristic model (i.e. model neglecting magnetic saturation)
NLM-model:	Nonlinear magnetic characteristic model (i.e. model accounting for magnetic saturation)
LM-CF strategy:	Control strategy based on LM-model with constant flux reference (i.e. standard strategy)
LM-OF strategy:	Control strategy based on LM-model, including optimal flux generator
NLM-CF strategy:	Control strategy based on NLM-model, involving constant flux reference
NLM-OF:	Strategy based on NLM-model with optimal flux generator (i.e. new control strategy)
SDOF:	State dependent optimal flux reference (i.e. newly proposed optimal flux generator)
OCF:	Optimal current–flux characteristic

The paper is organized as follows: the induction machine model is presented in Section 2. In Section 3, the proposed control strategy is described and a flux reference optimization law is developed. The machine speed and flux controller is designed and formally analyzed in Section 4. The controller performances are illustrated by simulation in Section 5. A conclusion and reference list end the paper. For convenience, all acronyms used throughout are described in Table 1.

2. Induction motor modeling

In Ouadi et al. (2004), a model accounting for the saturation nature of the machine magnetic characteristic (Fig. 1) has been developed and experimentally validated using a 7.5 KW induction motor. This model, named *NLM* throughout the paper, is defined by the following fifth order state-space representation:

$$\dot{i}_{s\alpha} = -a_2 i_{s\alpha} + \delta\phi_{r\alpha} + a_3 p\Omega\phi_{r\beta} + a_3 u_{s\alpha} \tag{1a}$$

$$\dot{i}_{s\beta} = -a_2 i_{s\beta} - a_3 p\Omega\phi_{r\alpha} + \delta\phi_{r\beta} + a_3 u_{s\beta} \tag{1b}$$

$$\dot{\phi}_{r\alpha} = a_1 i_{s\alpha} - L_{seq}\delta\phi_{r\alpha} - p\Omega\phi_{r\beta} \tag{2a}$$

$$\dot{\phi}_{r\beta} = a_1 i_{s\beta} - L_{seq}\delta\phi_{r\beta} + p\Omega\phi_{r\alpha} \tag{2b}$$

$$\dot{\Omega} = \frac{p}{J}(\phi_{r\alpha} i_{s\beta} - \phi_{r\beta} i_{s\alpha}) - \frac{T_L}{J} - \frac{f}{J}\Omega \tag{3}$$

where $i_{s\alpha}, i_{s\beta}$, are the $\alpha\beta$-components of the stator current, (state variables); $\phi_{r\alpha}, \phi_{r\beta}$ the rotor flux $\alpha\beta$-components, (state variables); Ω the motor speed, (state variable); $u_{s\alpha}, u_{s\beta}$ the $\alpha\beta$-components of the stator voltage, (control inputs); R_s, R_r the stator and rotor resistances; T_L the load torque; f the friction coefficient; p the number of pole pairs; and L_{seq} the equivalent inductance (of both stator and rotor leakage) as seen from the stator.

In (1)–(3), the real constants a_i's are defined as follows:

$$a_1 = R_r, a_2 = \frac{R_s + R_r}{L_{seq}}, a_3 = \frac{1}{L_{seq}}$$

Furthermore, δ is a function of the rotor flux norm (see Fig. 2). In Ouadi et al. (2004), this dependence was represented by a