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Fault-tolerant cruise control of electric vehicles with induction motors

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ABSTRACT

A fault-tolerant control scheme is proposed for the cruise control of electric vehicles (trains, cars) that make use of induction motors. It relies on a rotor speed reference generator and on a flux observer which is adaptive with respect to the uncertain rotor and stator resistances and to the load torque as well. The closed loop on-line identification of those three critical uncertain parameters allows for: (i) on-line estimating and imposing the motor flux modulus reference value which minimizes power losses at steady-state and improves power efficiency; (ii) the on-line detection of speed sensor faults as well as the fast switching on redundant motor speed sensors. CarSim simulations illustrate the effectiveness of the proposed approach.

1. Introduction

Fully-automated electric vehicles powered by electric motors constitute a green, energy-efficient, secure and safe transport technology. Most existing electric vehicles, including trains, subways, buses and cars, make use of three-phase induction motors since their inherent regenerative braking capability makes them ideal for green and highly energy-efficient electric traction. High maximum speed, simple cooling arrangement with enclosed frames, high uniform torque with inherent overload management, high power-weight ratio, low cost-power ratio are additional advantages. In electrical vehicle applications, high performance involving accurate motor parameter estimation as well as operation continuity involving tolerance to motor speed sensor faults are key features (see Benbouzid, Diallo, & Zeraoulia, 2007; Bennet, Patton, & Daley, 1999; Diallo, Benbouzid, & Makouf, 2004; Guzinski, Abu-Rub, Diguet, Krzeminski, & Lewicki, 2010, 2009; Lee & Ryu, 2003; Romero & Seron, 2010; Romero, Seron, & De Doná, 2010; Wang, Pekarek, & Fahimi, 2006; Zidani, Diallo, Benbouzid, & Berthelot, 2007). Rotor and stator resistances along with load torque are typically uncertain in induction motors: motor heating makes the winding resistances vary during operation whereas the load torque depends on operating conditions. Knowledge of rotor resistance, stator resistance and load torque is crucial for achieving power loss minimization of induction motors that are controlled by indirect field oriented controls (Marino, Scalzi, Tomei, & Verrelli, 2010a) since all these parameters appear in the expression of the flux modulus minimizing power losses at steady-state. Rotor resistance is additionally crucial for obtaining field orientation and flux modulus tracking. Accurate critical motor parameter identification (winding resistances and load torque) is therefore to be guaranteed in order to obtain high dynamic performance and to achieve high power efficiency. When induction motor thermal models are not available, the on-line estimation of the three critical parameters is inherently linked to the estimation of the motor fluxes: they appear in the stator current dynamics that are typically used to construct adaptive observers. Several adaptive observers have been proposed in the literature since 1978: see for instance Castaldi, Geri, Montanari, and Tilli (2005), Hasan and Husain (2009), Jeon, Oh, and Choi (2002), Kenné, Simo, Lamnabhi-Lagarrigue, Arzandé, and Vannier (2010), Marino, Tomei, and Verrelli (2011), Najafabadi, Salmasi, and Jabehdar-Maralani (2011) and Ţiclea and Besançon (2006) and references therein. The adaptive rotor flux observer presented in Marino et al. (2011) is, in particular, considered in this paper since it is simultaneously characterized by: (i) the ability of on-line estimating the rotor fluxes along with the three criticalparameters; (ii) an overall structural simplicity with no use of sign functions, high gains or output time derivatives which lead to well-known implementation difficulties and high noise sensitivity; (iii) persistency of excitation conditions which are naturally related to motor observability and parameter identifiability and are satisfied in the typical case of constant motor speed and flux modulus and non-zero electro-magnetic torque; (iv) exponential convergence properties which imply a certain degree of robustness; (v) the ability of detecting speed sensor faults in typical operating conditions (see Marino et al., 2012a) with

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avoidance of false fault detections due to uncertainties in the three critical parameters.

In this paper, on the basis of recent results on induction motor control (Marino, Scalzi, Tomei, & Verrelli, 2012b) and on the basis of the adaptive observer presented in Marino et al. (2011) (with its fault detection properties), a fault-tolerant indirect field oriented control scheme is proposed for the cruise control of electric vehicles powered by induction motors. Three specific original contributions can be summarized.

- A novel cruise control architecture (preliminary results can be found in Marino et al., 2012b) which generalizes the classical control schemes by transforming the vehicle speed reference into a suitable motor speed reference.
- The possibility of on-line estimating and imposing, even in the presence of critical parameter uncertainties, the motor flux modulus reference value which minimizes power losses at steady-state and improves power efficiency and mileage between battery charges (see Marino, Tomei, & Verrelli, 2010b).
- The possibility of on-line detecting speed sensor faults for the fast switching on redundant motor speed sensors so that high performance operations are preserved (Marino et al., 2012a).

Experimental results are first reported with the aim of illustrating the speed sensor fault-detection properties of the proposed adaptive observer. Simulations are finally carried out on a CarSim A-model vehicle which takes into account the combined lateral and longitudinal tire forces and tire dynamics. The simulations show that the performance of the proposed fault-tolerant cruise control strategy: the most severe and typical one that is described and reported in Benbouzid et al. (2007), Campos-Delgado, Espinoza-Trejo, and Palacios (2008), Najafabadi et al. (2011) and Tabbache, Benbouzid, Kheloui, and Bourgeot (2011) is in particular considered in experiments and simulations.

The paper is organized as follows: in Section 2, the induction motor model is introduced and the model-based approach to speed sensor fault detection is discussed; in Section 3, the adaptive observer is presented and its speed sensor fault detection properties are theoretically and experimentally described; in Section 4, the fault-tolerant cruise control for electric vehicles is finally proposed and its effectiveness is tested by CarSim simulations.

2. Induction motor modeling and fault detection issues

In this section the well known model of induction motors is introduced. A model-based approach to speed sensor fault-detection problems is then discussed.

2.1. Induction motor modeling

Assuming linear magnetic circuits, the dynamics of a balanced non-saturated induction motor with one pole pair in a fixed reference frame attached to the stator are given by the well known fifth-order model (see for instance Marino, Tomei, & Verrelli, 2010a and references therein)

$$\frac{d\omega}{dt} = \mu(\psi_{ra} i_{sb} - \psi_{rb} i_{sa}) - \frac{T_L}{J}$$
$$\frac{d\psi_{ra}}{dt} = -\alpha\psi_{ra} - \omega\psi_{rb} + \alpha M i_{sa}$$
$$\frac{d\psi_{rb}}{dt} = -\alpha\psi_{rb} + \omega\psi_{ra} + \alpha M i_{sb}$$
$$\frac{di_{sa}}{dt} = -\left(\frac{R_s}{\sigma} + \beta\alpha M\right) i_{sa} + \frac{1}{\sigma} u_{sa} + \beta\alpha\psi_{ra} + \beta\omega\psi_{rb}$$
$$\frac{di_{sb}}{dt} = -\left(\frac{R_s}{\sigma} + \beta\alpha M\right) i_{sb} + \frac{1}{\sigma} u_{sb} + \beta\alpha\psi_{rb} - \beta\omega\psi_{ra}, \tag{1}$$

in which: ω is the rotor speed, (ψ_{ra},ψ_{rb}) are the rotor fluxes, (i_{sa},i_{sb}) are the stator currents, (u_{sa},u_{sb}) are the stator voltages in a fixed reference attached to the stator. The constant model parameters are: load torque T_L; motor moment of inertia J; rotor and stator windings resistances (R_r,R_s) and inductances (L_r,L_s); mutual inductance M. To simplify notations the reparameterization: $\alpha = R_r/L_r$, $\beta = M/\sigma L_r$, $\mu = M/JL_r$, $\sigma = L_s(1-M^2/L_sL_r)$ is used. The rotor fluxes (ψ_{ra},ψ_{rb}) are unmeasured variables since flux sensors are usually not available while the parameters T_L, α and R_s are typically uncertain owing to load torque dependence on applications and owing to resistance variations which depend on motor heating.

2.2. Fault detection issues

This paper addresses the problem of detecting rotor speed sensor failures or malfunctions with the aim of guaranteeing fault-tolerant, high-efficiency cruise control of electric vehicles. Encoders are typically used in speed-controlled induction motors. They can exhibit faulty behaviours: intermittent sensor connection; complete sensor outage; DC bias in sensor measurements; sensor gain drop (see Campos-Delgado et al., 2008). The most severe faults are the first two ones since they imply a momentary or complete lack of information. They can lead to closed loop instability if no proper action is performed. A model-based approach to fault diagnosis (see for instance Isermann, 2011; Ding, 2008) is proposed in this paper. Its idea relies on the assumption that certain process signals (i.e. measured stator currents and voltages and measured rotor speed) carry information about the faults of interest (Marino et al., 2012a). On the basis of those measurements from (and knowledge of) the system, a "residual signal" is generated: it is zero when no fault is present and non-zero when faults occur (see also Bennet et al., 1999). The key-point of this section is based on specific observation/identification structural difficulties which arise when only stator currents and voltages are measured and uncertain parameters (in particular rotor resistance) are to be estimated. When the motor typically operates at constant rotor speed and flux modulus with non-zero load torque to minimize power losses and maximize power efficiency at steady-state (see Marino et al., 2010b), the simultaneous estimation of rotor speed and rotor resistance cannot be achieved (see Ha & Lee, 2000 as well as Marino et al., 2010a and references therein). Those observation/identification structural difficulties can be used to our advantage. Assume that the motor is operating at constant rotor speed and flux modulus with non-zero load torque: any flux observer which is adaptive with respect to rotor and stator resistances, uses the (constant) measured speed ω_m and provides an exponentially convergent rotor resistance estimate when $\omega_m \equiv \omega$ is able to exponentially identify, in the presence of critical parameter uncertainties, the linear combination

$$\mathcal{L}_e = R_r + \gamma(\omega - \omega_m). \tag{2}$$

If the rotor speed is measured and no rotor speed sensor fault occurs, i.e. $\omega \equiv \omega_m$, estimating $\mathcal{L}_e$ coincides with estimating R_r. On the other hand, in the presence of speed sensor failures, estimating $\mathcal{L}_e$ coincides with estimating a quantity which, depending on $(\omega - \omega_m)$, may be larger or smaller than any admissible $R_r \in [R_{rm}, R_{rM}]$ for the specific motor in consideration, that is

$$R_r + \gamma(\omega - \omega_m) < R_{rm} \tag{3}$$