Rotor Speed Sensor Fault Detection in Induction Motors

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Abstract: The problem of detecting a speed sensor fault in induction motor applications with load torque and rotor/stator resistances uncertainties is addressed. It is shown that in typical operating conditions involving constant rotor speed and flux modulus and non-zero load torque, a constant non-zero (sufficiently large) difference between the measured speed and the actual speed may be on-line identified by an adaptive flux observer which incorporates a convergent rotor resistance identifier and relies on the measured rotor speed and stator currents/voltages.

1 INTRODUCTION

Three-phase induction motors are widely used for electric railway and automotive traction (Hill, 1994) since they offer several advantages such as no commutator, no brushes, no rotor windings in squirrel cage motors, simple rugged structure, inherent regenerative braking capability, ability of tolerating heavy overloading and of producing high torques with low weights, small sizes, and low rotating masses. In high impact automotive applications (see Rehman, 2008) such as electrical and hybrid electrical vehicles, the operation continuity is a key feature and high reliability of the drive system should be guaranteed (see Benbouzid et al., 2007). On the other hand, traction main drives are often equipped with rotor speed sensors (Guzinski et al., 2009) which are used by classical induction motor control schemes such as direct or indirect field oriented controls (see Marino et al., 2010b) for recent adaptive results). In the case of rotor speed sensor fault, a proper and prompt fault detection is required so that an effective action can be performed and the fault effect is not widely propagated with a resulting hard system failure.

The idea underlying a model-based approach to fault diagnosis (see for instance (Isermann, 2011) and (Ding, 2008)) relies on the assumption that certain process signals carry information about the faults of interest. The gist of the approach is then to generate, on the basis of measurements from (and knowledge of) the system, a set of "residual signals" which are zero when no fault is present and non-zero when faults occur (Bennet et al., 1999). However several difficulties naturally arise for the specific application to induction motors: induction motor dynamics are nonlinear; flux measurements are not available; three critical parameters, namely rotor and stator resistances (which vary during operations due to motor heating) and load torque (which depends on applications), are typically uncertain and are required to be on-line estimated.

A first intuitive solution ($\mathcal{IS}$) to speed sensor fault detection problems relies on designing an adaptive flux/speed observer which does not use the measured speed but only stator currents and voltages measurements (see (Guzinski et al., 2010) and (Guzinski et al., 2009)). The gist of the above design is then to compare the measured speed with the estimated one with the aim of identifying the possibly occurring speed sensor fault. Since suitable identifiers for the uncertain parameters are to be incorporated in the adaptive observer in order to avoid false fault detections, the drawback of the above approach is then constituted by the well-known identifiability and observability issues which arise when only stator currents and voltages are measured. It is in fact well-established that when the motor 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 Marinoet al., 2010b), the simultaneous estimation of rotor speed and rotor resistance cannot be achieved (see (Ha and Lee, 2000), (Marino et al., 2008), as well as (Marino et al., 2010a)) and references therein) since only a linear combination

$$\mathcal{L} \;=\; R_r + \gamma\omega$$

of the rotor resistance R_r and speed ω (along with the real γ) can be on-line identified by stator currents

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and voltages measurements. This structural difficulty may be used to our advantage by noting that when the (constant) measured speed ω_m is used by a suitable adaptive flux observer $\mathcal{AFO}$, the identifiable linear combination becomes

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

If the rotor speed is measured and no speed sensor fault 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

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

or

$$R_r + \gamma(\omega - \omega_m) > R_{rM}.$$

In this case a speed sensor fault may be on-line identified by designing a speed measurement-based adaptive observer and by monitoring the estimate of $\mathcal{L}_e$ on the basis of the boundary values R_{rm} and R_{rM}.

The aim of this paper is to show that an adaptive flux observer $\mathcal{AFO}$ which incorporates a convergent rotor resistance identifier and relies on the measured rotor speed and stator currents/voltages may be effectively used to on-line identify a constant non-zero (sufficiently large) difference $\omega - \omega_m$ in typical operating conditions involving non-zero load torque and constant rotor speed and flux modulus. In particular, denoting by $\alpha \in [\alpha_m, \alpha_M]$ ($\alpha_m = L_r R_{rm}$, $\alpha_M = L_r R_{rM}$) the ratio between the rotor resistance R_r and the rotor inductance L_r and by $\hat{\alpha}$ its estimate (provided by the $\mathcal{AFO}$), we will show that a residual signal for the speed sensor fault detection may be chosen as the steady-state distance of $\hat{\alpha}(t)$ from the compact set $[\alpha_m, \alpha_M]$, i.e.

$$\lim_{t \to +\infty} \mathrm{dist}(\hat{\alpha}(t); [\alpha_m, \alpha_M]).$$

A similar idea (though not analytically motivated) has been also recently presented in Najafabadi et al. (2011) even though it relies on an observer which is adaptive with respect to the rotor resistance only. In contrast to Najafabadi et al. (2011), we propose a candidate adaptive flux observer belonging to the set of all adaptive flux observers which provide convergent estimates of the rotor resistance despite uncertainties in critical parameters such as load torque and stator resistance. This is to avoid false fault detections which may be related to uncertainties in those critical parameters. With this respect, among the adaptive observers which have been proposed in the literature since 1978 (see for instance (Castaldi et al., 2005), (Hasan and Husain, 2009), (Jeon et al., 2002), (Kenné et al., 2010), (Marino et al., 2000), (Marino et al., 2011), (Najafabadi et al., 2011), (Ţiclea and Besançon, 2006) and references therein), we consider in this paper the one presented in Marino et al. (2011) which is simultaneously characterized by: i) 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; ii) persistency of excitation conditions which are naturally related to motor observability and parameter identifiability and are guaranteed to be satisfied in the typical case of constant motor speed and flux modulus and non-zero electromagnetic torque; iii) exponential convergence properties guaranteeing a certain degree of robustness. It is constituted by an adaptive flux observer which is able to estimate the motor fluxes and to identify the rotor resistance and by a stator resistance identifier whose design is performed on a different time scale in order to isolate its estimation from the estimation of motor fluxes and rotor resistance (see also (Jadot et al., 2009), (Marino et al., 2010c)) for a similar approach to parameter estimation in induction motors). Simulation and experimental results illustrate the effectiveness of the proposed solution and show satisfactory fault detection performances. Such a speed sensor fault detector constitutes a first step toward the design of effective fault-tolerant control architectures which involve output feedback adaptive tracking controls (Marino et al., 2010b) minimizing power losses in conjunction with sensorless adaptive tracking controls (Marino et al., 2010c) imposing rotor speed observability and resistance identifiability. Those fault-tolerant architectures may be of special interest for speed-controlled traction applications in which induction motor controls are required to tolerate rotor speed sensor faults (see (Benbouzid et al., 2007), (Guzinski et al., 2010), (Guzinski et al., 2009)) and to maintain at the same time high power efficiency at every speed (see (Bennet et al., 1999), (Diallo et al., 2004), (Lee and Ryu, 2003), (Romero et al., 2010), (Wang et al., 2006) for the general problem of designing fault-tolerant induction motor controls).

2 PHYSICAL 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 et al., 2010a) and references therein)

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

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 we use the reparameterization: $\alpha = \frac{R_r}{L_r}$, $\beta = \frac{M}{\sigma L_r}$, $\mu = \frac{M}{JL_r}$, $\sigma = L_s(1 - \frac{M^2}{L_s L_r})$. 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. We will only assume, in the following, the boundedness of state and input variables while any restriction concerning the boundedness of stator currents integrals, which has been proposed for the design of similar adaptive flux observers in Jeon et al. (2002), (Marino et al. (2000), is not required.

3 OBSERVER DESIGN

The first idea in Marino et al. (2011) is to introduce the variables $z_a = i_{sa} + \beta\psi_{ra}$, $z_b = i_{sb} + \beta\psi_{rb}$ so that the motor electro-magnetic equations in (1) become

$$
\begin{aligned}
\dot{z}_a &= -\frac{R_s}{\sigma} i_{sa} + \frac{1}{\sigma} u_{sa} \\
\dot{z}_b &= -\frac{R_s}{\sigma} i_{sb} + \frac{1}{\sigma} u_{sb} \\
\frac{di_{sa}}{dt} &= -\frac{R_s}{\sigma} i_{sa} - \alpha(1+\beta M) i_{sa} - \omega i_{sb} + \alpha z_a \\
&\quad + \omega z_b + \frac{1}{\sigma} u_{sa} \\
\frac{di_{sb}}{dt} &= -\frac{R_s}{\sigma} i_{sb} - \alpha(1+\beta M) i_{sb} + \omega i_{sa} + \alpha z_b \\
&\quad - \omega z_a + \frac{1}{\sigma} u_{sb}.
\end{aligned}
\tag{2}
$$

The advantage of using the (z_a, z_b) variables, which are physically related to the stator fluxes, is that their dynamics depend neither on the unmeasured rotor fluxes nor on the uncertain rotor resistance. On the basis of model (2), the following observer is designed (k_i is a positive design parameter):

$$
\begin{aligned}
\dot{\hat{i}}_{sa} &= -\frac{\hat{R}_s}{\sigma} i_{sa} - \hat{\alpha}(1+\beta M) i_{sa} - \omega \hat{i}_{sb} + \hat{\alpha}\hat{z}_a \\
&\quad + \omega\hat{z}_b + \frac{u_{sa}}{\sigma} + k_i(i_{sa} - \hat{i}_{sa}) \\
\dot{\hat{i}}_{sb} &= -\frac{\hat{R}_s}{\sigma} i_{sb} - \hat{\alpha}(1+\beta M) i_{sb} + \omega \hat{i}_{sa} + \hat{\alpha}\hat{z}_b \\
&\quad - \omega\hat{z}_a + \frac{u_{sb}}{\sigma} + k_i(i_{sb} - \hat{i}_{sb}) \\
\dot{\hat{z}}_a &= -\frac{\hat{R}_s}{\sigma} i_{sa} + \frac{u_{sa}}{\sigma} + v_a \\
\dot{\hat{z}}_b &= -\frac{\hat{R}_s}{\sigma} i_{sb} + \frac{u_{sb}}{\sigma} + v_b
\end{aligned}
\tag{3}
$$

which is a copy of system (2) with: i) the estimates $(\hat{z}_a, \hat{z}_b, \hat{\alpha}, \hat{R}_s)$ in place of the unmeasured/uncertain (z_a, z_b, α, R_s); ii) stabilizing terms on the current estimation errors $(i_{sa} - \hat{i}_{sa})$, $(i_{sb} - \hat{i}_{sb})$; iii) the compensating terms v_a, v_b yet to be designed. According to the stability analysis in Marino et al. (2011), the estimation laws for $\hat{\alpha}$ and $\hat{R}_s$ and the feedback terms v_a, v_b are chosen as

$$
\begin{aligned}
\dot{\hat{\alpha}} &= -k_\alpha\Big[[(1+\beta M) i_{sa} - \hat{z}_a]\tilde{i}_{sa} + [(1+\beta M) i_{sb} - \hat{z}_b]\tilde{i}_{sb}\Big] \\
\dot{\hat{R}}_s &= -k_R\,(v_a i_{sa} + v_b i_{sb}) \\
v_a &= -k_z\,(\omega\tilde{i}_{sb} - \hat{\alpha}\tilde{i}_{sa}) \\
v_b &= k_z\,(\omega\tilde{i}_{sa} + \hat{\alpha}\tilde{i}_{sb})
\end{aligned}
\tag{4}
$$

in which $\tilde{i}_{sa} = i_{sa} - \hat{i}_{sa}$, $\tilde{i}_{sb} = i_{sb} - \hat{i}_{sb}$ are the stator current estimation errors, k_z and k_α are positive design parameters, k_R is a sufficiently small positive design parameter.

The two-time-scale arguments in Marino et al. (2011), under certain identifiability assumptions at steady-state, allow for isolating the estimation of the stator resistance from the estimation of motor fluxes (achieved through the estimation of (z_a, z_b)) and rotor resistance so that the following persistency of excitation condition:

$\mathcal{P}_e$: *there exist two positive reals t_p and k_p such that the persistency of excitation condition (I_3 is the 3×3 identity matrix)*

$$
\int_t^{t+t_p} \Gamma^{\mathrm{T}}(\tau)\Gamma(\tau)\,d\tau \;\geq\; k_p I_3, \quad \forall\, t \geq 0 \tag{5}
$$

holds with

$$
\Gamma = \begin{bmatrix} \alpha & \omega & \beta(\psi_{ra} - M i_{sa}) \\ -\omega & \alpha & \beta(\psi_{rb} - M i_{sb}) \end{bmatrix}
$$

is obtained. Inequality (5) is naturally related to motor observability and parameter identifiability: when the rotor speed and the rotor flux modulus are constant and the load torque is zero so that $\psi_{ra} = M i_{sa}$

and $\psi_{rb} = Mi_{sb}$, it cannot be satisfied; when a positive load torque is applied and when the rotor speed and the rotor flux modulus are constant with $\psi_{ra}^2 + \psi_{rb}^2 = c_\psi > 0$, it is satisfied.

The gist of the estimation design in Marino et al. (2011) and the required assumptions can be simply explained in the following terms: if the adaptive observer (3)-(4) (with no stator resistance identifier) is used with a constant value of the stator resistance that is slightly different from its actual value, then a non-zero steady-state solution appears that causes a suitable measured output function $s_\pi = v_a i_{sa} + v_b i_{sb}$ to be, in first approximation, monotone with respect to the R_s-estimation error $\tilde{R}_s = R_s - \hat{R}_s$; thus, by adjusting the R_s-estimate $\hat{R}_s$ on the basis of this output function (slowly, in order not to deviate too much from the steady-state solution) one can obtain the correct estimation of R_s and the consequent exponential convergence to zero of all the estimation errors $\tilde{i}_{sa}$, $\tilde{i}_{sb}$, $z_a - \hat{z}_a$, $z_b - \hat{z}_b$, $\alpha - \hat{\alpha}$, $\tilde{R}_s$. Exponential rotor flux recovering can be finally obtained by

$$\begin{bmatrix} \hat{\psi}_{ra} \\ \hat{\psi}_{rb} \end{bmatrix} = -\frac{1}{\beta} \begin{bmatrix} \hat{i}_{sa} - \hat{z}_a \\ \hat{i}_{sb} - \hat{z}_b \end{bmatrix}$$

where the filtered estimates $(\hat{i}_{sa}, \hat{i}_{sb})$ are preferred to the measured (i_{sa}, i_{sb}) for practical implementation issues. The following second-order load torque identifier (k_ω and k_T are positive design parameters):

$$\begin{aligned} \dot{\hat{\omega}} &= \mu(\hat{\psi}_{ra} i_{sb} - \hat{\psi}_{rb} i_{sa}) - \frac{\hat{T}_L}{J} + k_\omega(\omega - \hat{\omega}) \\ \dot{\hat{T}}_L &= -k_T(\omega - \hat{\omega}) \end{aligned}$$

is finally proposed in Marino et al. (2011). It can be used in conjunction with the adaptive observer (3)-(4) to provide an exponentially convergent estimate of the load torque once convergent estimates of rotor fluxes have been obtained. The proof, which is reported in Marino et al. (2010a), is based on the quadratic function

$$V_T = \frac{1}{2k_T J}\tilde{T}_L^2 + \frac{1}{2}\tilde{\omega}^2 + \varepsilon\tilde{\omega}\tilde{T}_L$$

in which $\tilde{\omega} = \omega - \hat{\omega}$, $\tilde{T}_L = T_L - \hat{T}_L$ and $\varepsilon > 0$ is a sufficiently small positive real.

4 SENSOR FAULT DETECTION

The aim of this section is to prove that a constant non-zero (sufficiently large) difference between the measured speed and the actual speed may be on-line identified by the adaptive flux observer (3)-(4) (in which the measured speed ω_m replaces the actual speed ω) in typical operating conditions involving non-zero load torque and constant rotor speed and flux modulus. To this purpose, we preliminary note that in those conditions we have

$$\begin{aligned} \overbrace{\psi_{ra}^2 + \psi_{rb}^2}^{\cdot} &\equiv 0 \\ \dot{\omega} &\equiv 0, \end{aligned}$$

from which we obtain

$$\begin{aligned} Mi_{sa} &= \psi_{ra} - c\psi_{rb} \\ Mi_{sb} &= \psi_{rb} + c\psi_{ra} \end{aligned} \tag{6}$$

with (ω_s is the slip speed [see (Marino et al., 2010a)])

$$c = \frac{T_L M}{J\mu c_\psi} = \frac{T_L L_r}{c_\psi} = \omega_s/\alpha.$$

By adding and subtracting in (2) suitable terms proportional to $\omega_e = \omega - \omega_m$ and by using (6), equations (2) can be equivalently rewritten as

$$\begin{aligned} \dot{z}_a &= -\frac{R_s}{\sigma} i_{sa} + \frac{1}{\sigma} u_{sa} \\ \dot{z}_b &= -\frac{R_s}{\sigma} i_{sb} + \frac{1}{\sigma} u_{sb} \\ \frac{\mathrm{d}i_{sa}}{\mathrm{d}t} &= -\frac{R_s}{\sigma} i_{sa} - \omega_m i_{sb} + \omega_m z_b + \frac{1}{\sigma} u_{sa} \\ &\quad + \alpha[z_a - (1+\beta M) i_{sa}] + \omega_e (z_b - i_{sb}) \\ \frac{\mathrm{d}i_{sb}}{\mathrm{d}t} &= -\frac{R_s}{\sigma} i_{sb} + \omega_m i_{sa} - \omega_m z_a + \frac{1}{\sigma} u_{sb} \\ &\quad + \alpha[z_b - (1+\beta M) i_{sb}] - \omega_e (z_a - i_{sa}) \end{aligned}$$

with the last two equations reading

$$\begin{aligned} \frac{\mathrm{d}i_{sa}}{\mathrm{d}t} &= -\frac{R_s}{\sigma} i_{sa} - \omega_m i_{sb} + \omega_m z_b + \frac{1}{\sigma} u_{sa} \\ &\quad + \left(\alpha + \frac{\omega_e}{c}\right)(z_a - (1+\beta M) i_{sa}) \\ \frac{\mathrm{d}i_{sb}}{\mathrm{d}t} &= -\frac{R_s}{\sigma} i_{sb} + \omega_m i_{sa} - \omega_m z_a + \frac{1}{\sigma} u_{sb} \\ &\quad + \left(\alpha + \frac{\omega_e}{c}\right)(z_b - (1+\beta M) i_{sb}). \end{aligned}$$

In other terms, in typical operating conditions involving non-zero load torque and constant rotor flux modulus and (measured and actual) speeds, an equivalent constant $\alpha_e = \alpha + \omega_e/c$ appears in the motor model (with ω_m in place of ω): it incorporates any possibly non-zero difference between the measured speed and the actual speed.

By virtue of the same analysis presented in Marino et al. (2011) and discussed in Section 3 (with ω_m in place of ω), the adaptive observer (3)-(4) is able to guarantee exponential convergence to zero of all the estimation errors $\tilde{i}_{sa}$, $\tilde{i}_{sb}$, $z_a - \hat{z}_a$, $z_b - \hat{z}_b$, $\alpha_e - \hat{\alpha}$, $\tilde{R}_s$

(provided that initial errors belong to the region of attraction of the origin for the error system dynamics). Exponential estimation of motor fluxes, equivalent α and stator resistance are therefore achieved. In particular, $\lim_{t\to+\infty} \text{dist}(\hat{\alpha}(t); [\alpha_m, \alpha_M])$ may be used as a residual signal for speed sensor fault detection since when rotor speed ω and flux modulus $\sqrt{\psi_{ra}^2 + \psi_{rb}^2}$ are constant along with the measured speed ω_m, the α-estimate $\hat{\alpha}(t)$ is guaranteed to exponentially converge to α_e. It is clear that only the speed sensor faults that lead to a value of α_e outside the compact set $[\alpha_m, \alpha_M]$ can be in this way identified. An estimate of ω_e (and therefore of the sensor failure magnitude) can be finally obtained according to

$$\frac{T_L L_r}{c_\psi}(\alpha_e - \alpha) \quad = \quad \omega_e$$

once the load torque (through the load torque identifier) and the rotor fluxes have been estimated.

5 SIMULATION RESULTS

The aim of this section is to illustrate the previously presented results even in the presence of time-varying perturbations of the motor resistances and step-wise variations of the load torque. To this purpose, the nonlinear adaptive observer (3)-(4) and the load torque identifier are simulated for the three-phase single pole pair 0.6-kW induction motor OE-MER 7-80/C in Marino et al. (2010a) whose parameters are: $J = 0.0075$ kgm^2, $R_s = 5.3$ Ohm, $R_r = 3.3$ Ohm, $L_s = 0.365$ H, $L_r = 0.375$ H, $M = 0.34$ H. The motor (with initial conditions $\psi_{ra}(0) = \psi_{rb}(0) = 0.1$ Wb) is illustratively controlled by the input-output feedback linearizing control reported in Section 2.4 of Marino et al. (2010a) (which relies on exact rotor speed and stator current measurements and on the perfect knowledge of all motor parameters). The rotor speed and the flux modulus are reported in Figure 1. The design parameters are chosen as (all the values are in SI units): $k_i = 120$, $k_z = 3$, $k_\alpha = 450$, $k_R = 0.1$, $k_\omega = 200$, $k_T = 100^2 J$. All the observer initial conditions are set to zero excepting for $\hat{\alpha}(0) = 9$ s^{-1} and $\hat{R}_s(0) = 5.4$ Ohm. For $t < 1.8$ s the measured speed is equal to the actual one ($\omega \equiv \omega_m$) while for $t \geq 1.8$ s a speed sensor fault occurs leading to $\omega - \omega_m = 0.4\omega$. The equivalent rotor resistance $R_e = L_r \alpha_e$ is thus equal to R_r for $t < 1.8$ s and equal to $R_r + \omega_e c_\psi / T_L$ for $t \geq 1.8$ s. The rotor fluxes, the load torque, the equivalent rotor resistance, the stator resistance along with the corresponding converging estimates are reported in Figures 2-5. Fast estimation is obtained: the speed sensor fault can be promptly identified by monitoring the estimated

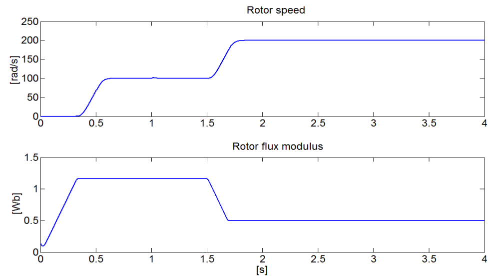

Figure 1: Rotor speed ω and flux modulus $\sqrt{\psi_{ra}^2 + \psi_{rb}^2}$.

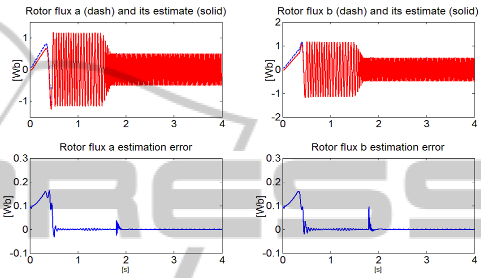

Figure 2: Rotor fluxes ψ_{ra}, ψ_{rb} (dash) and their estimates $\hat{\psi}_{ra}, \hat{\psi}_{rb}$ (solid); rotor fluxes ψ_{ra}, ψ_{rb} estimation errors.

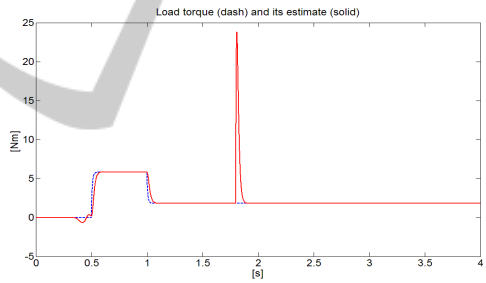

Figure 3: Load torque T_L (dash) and its estimate $\hat{T}_L$ (solid).

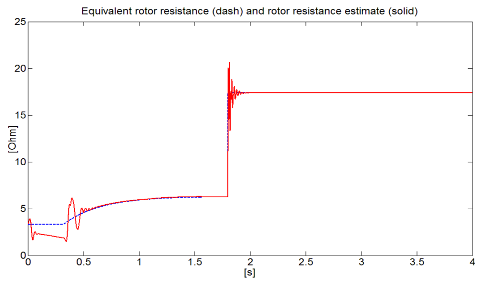

Figure 4: Equivalent rotor resistance R_{re} (dash) and its estimate $\hat{R}_r$ (solid).

rotor resistance on the basis of the available bounding values $R_{rm} = L_r \alpha_m = 2.8$ Ohm, $R_{rM} = L_r \alpha_M = 6.9$ Ohm. In order to illustrate the possibility of detecting false faults by using adaptive observers with no stator resistance identifier (as in (Najafabadiet al., 2011)), the same simulation is carried out in the presence of no speed sensor fault for the adaptive observer (3)-

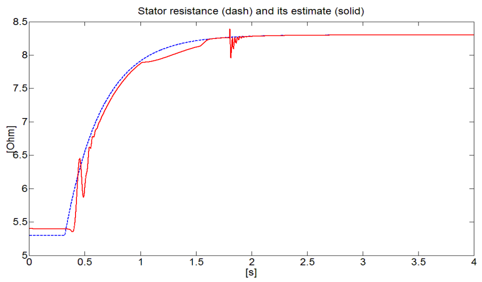

Figure 5: Stator resistance R_s (dash) and its estimate $\hat{R}_s$ (solid).

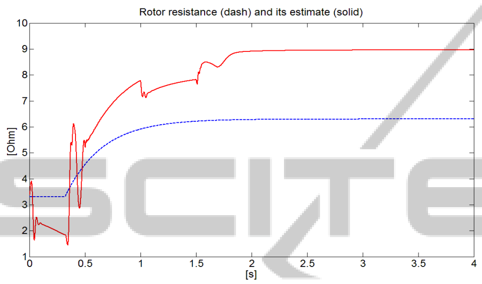

Figure 6: Observer with no R_s-adaptation: rotor resistance R_r (dash) and its estimate $\hat{R}_r$ (solid).

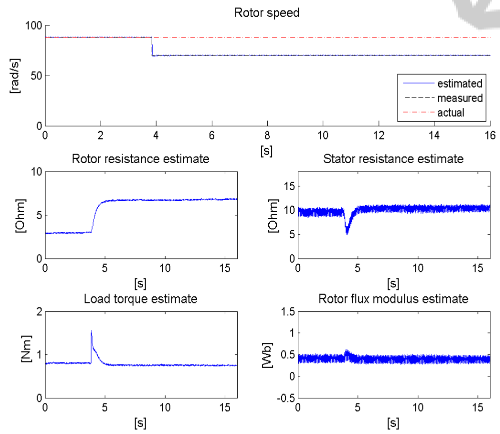

Figure 7: First experimental test ($\omega_m = 70$ rad/s, $\omega = 88$ rad/s).

(4) with the stator resistance value 5.4 Ohm in place of $\hat{R}_s$. As illustrated by Figure 6, a non-zero residual results even in the case of no speed sensor fault: this is only due to stator resistance uncertainties and motivates the use of adaptive observers which provide convergent rotor resistance estimates despite stator resistance uncertainties.

6 EXPERIMENTAL RESULTS

In this section we present the results of three experimental tests which have been carried out with reference to a 0.25 kW C4T34FB5B Leeson induction motor driven by a 20 kHz PWM-based open loop voltage/frequency control (61 V, 16.7 Hz). The applied load torque, which is proportional to the induction motor speed, is provided by the WSM-3-32-1 Sangalli Servomotori DC permanent magnet motor directly connected to the shaft of the induction motor. The nonlinear adaptive observer (3)-(4) and the load torque identifier are executed (at 12.5 kHz) when the motor has reached its steady-state. The nominal values of the parameters (provided by the manufacturer) $L_s = 0.268$ H, $L_r = 0.298$ H, $M = 0.258$ H, $J = 0.005$ kgm^2 are used, the control gains (all the values are in SI units) $k_i = 600$, $k_z = 3$, $k_\alpha = 10$, $k_R = 0.65$, $k_\omega = 100$, $k_T = 5$ are chosen while zero initial conditions, excepting for $\hat{\alpha}(0)$ and $\hat{R}_s(0)$ (equal to 12.75 s^{-1} and 10.45 Ohm) are set. The first test, whose steady-state results are reported in Figure 7, involves a partial speed sensor fault ($\omega_m = 70$ rad/s, $\omega = 88$ rad/s) occurring at $t = 3.84$ s. The second test, whose steady-state results are reported in Figure 8, involves a larger partial speed sensor fault ($\omega_m = 44$ rad/s, $\omega = 88$ rad/s) occurring at $t = 2.02$ s. The third test, whose steady-state results are reported in Figure 9, finally involves a full speed sensor fault ($\omega_m = 0$ rad/s, $\omega = 88$ rad/s) occurring at $t = 1.66$ s. All the three tests confirm the theoretical results presented in the paper: as expected, the speed sensor fault can be promptly identified ($R_{rM} = 6$ Ohm) by monitoring the estimated rotor resistance which converges to α_e.

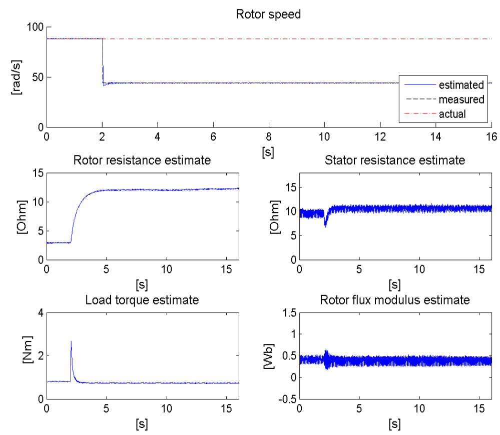

Figure 8: Second experimental test ($\omega_m = 44$ rad/s, $\omega = 88$ rad/s).

7 CONCLUSIONS

A constant non-zero (sufficiently large) difference between the measured speed and the actual speed may be on-line identified, even in the presence of uncertainties in load torque and rotor/stator resistances, in

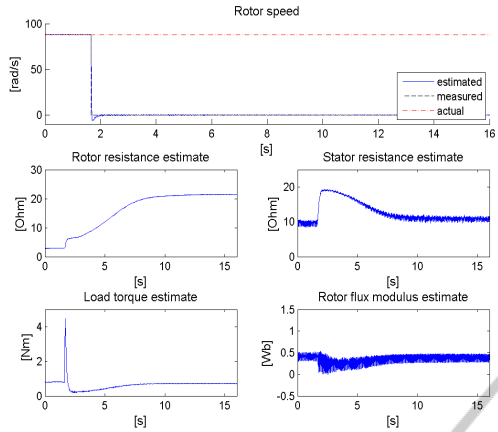

Figure 9: Third experimental test ($\omega_m = 0$ rad/s, $\omega = 88$ rad/s).

typical operating conditions involving non-zero load torque, constant rotor speed and flux modulus. An adaptive flux observer which incorporates a convergent rotor resistance identifier and relies on the measured rotor speed and stator currents/voltages is used to this purpose. A relevant consequence of the presented analysis is that rotor fluxes (and therefore motor torque), load torque and stator resistance can be actually estimated even in the presence of speed sensor faults.

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