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Steady-state speed sensor fault detection in induction motors with uncertain parameters: A matter of algebraic equations

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ABSTRACT

This paper moves in the context highlighted in the recent literature, in which full and partial rotor speed sensor faults in induction motors with uncertain parameters can be detected by a single adaptive observer. Certain relevant experimental evidences concerning the use of such single adaptive observer in the aforementioned context, however, are yet to be theoretically motivated. Such evidences go beyond the already presented analyses and refer to the convergence of the resulting observer estimates under generating operations. In this paper, we present an algebraic equations-based analysis that extends any previous one, by providing a definite answer to the above question. It simultaneously clarifies any structural intrinsic limitation that is related to previously proposed approaches. The key point relies on deriving the explicit expressions for two admissible motor model solutions, which are characterized by the same output (rotor speed and stator currents) and input (stator voltages) profiles and whose existence is definitely linked to the adaptive observer behaviour in speed sensor fault detection scenarios.

1. Introduction

The induction motor is one among the most widespread electric machines. This is due to its good self-starting capability, simple and rugged structure, reliability and good over-loading performance. The actual DSP and power electronics components allow for low cost, field oriented control-based electrical drives. They exhibit dynamic behaviours that are similar to the ones guaranteed by permanent magnet brushless machines. In this respect, speed/position sensors are typically used in speed-controlled induction motors. They can present faulty or incorrect operations[1] : intermittent sensor connection, DC bias in sensor measurements or sensor gain drop. The most severe fault is, however, the complete sensor outage, which implies a complete lack of speed information and may lead to closed loop instability, especially when it is not quickly recognized and no proper action is performed. The problem of detecting full speed sensor faults (under steady-state conditions) is a relevant one: induction motors with the ability of detecting speed sensor faults are certainly more rugged and reliable. Those features are particularly advantageous in electric vehicles applications, in which operation continuity involving tolerance to motor speed sensor faults is a key feature (see Benbouzid, Diallo, and Zeraoulia (2007), Guzinski, Abu-Rub, Diguet, Krzeminski, and Lewicki (2010), Guzinski, Diguet, Krzeminski, Lewicki, and Abu-Rub (2009), Zidani, Diallo, Benbouzid, and Berthelot (2007), Bennet, Patton, and Daley (1999), Diallo, Benbouzid, and Makouf (2004), Lee and Ryu (2003), Raisemche, Boukhnifer, Larouci, and Diallo (2014), Romero and Seron (2010), Romero, Seron, and De Doná (2010) and Wang, Pekarek, and Fahimi (2006)), with safety playing a crucial role.

The idea underlying a model-based approach to fault diagnosis relies on the assumption that certain process signals carry information about the faults of interest. The gist of the approach is to generate,

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[1] The reader is referred to the recent paper (Riera-Guasp, Antonino-Daviu, & Capolino, 2015) for an exhaustive review on fault detection in electrical machines and to Mustafa, Nikolakopoulos, Gustafsson, and Kominiak (2016), Mustafa, Varagnolo, Nikolakopoulos, and Gustafsson (2016), Martin-Diaz, Morinigo-Sotelo, Duque-Perez, and de J. Romero-Troncoso (2017) and Giantomassi, Ferracuti, Iarlori, Ippoliti, and Longhi (2015) (and references therein) for more general kinds of faults affecting induction motors.

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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 (see the general concepts in Ding (2008) and Isermann (2011) and observer-based applications in Chakraborty and Verma (2015), Alwi and Edwards (2014), Guzinski et al. (2010), Kommuri, Rath, Veluvolu, Defoort, and Soh (2015) and Raisemche et al. (2014)). Intuitive solutions to the speed sensor fault-detection problem in induction motors then rely on:

(i) the design of adaptive flux/speed observers that only use the measurements of stator currents and voltages and provide speed estimates;
(ii) the comparison of 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 (in particular rotor and stator resistances and load torque) are to be necessarily incorporated into such adaptive observers in order to avoid false fault detections, the drawback – and failing cause – of the aforementioned approach consists of the well-known identifiability and observability issues that arise when only stator currents and voltages are measured. It is in fact well-established that, when the motor typically operates at constant rotor speed ω^* and flux modulus ψ^* with constant non-zero load torque T_L (and resulting non-zero speed of the rotor flux vector) – to minimize power losses and maximize power efficiency at steady-state – the simultaneous estimation of rotor speed and rotor resistance cannot be achieved. This is clearly expressed by constraint (85) and related discussion in Vaclavek, Blaha, and Herman (2013). In fact, under those conditions, only a linear combination $\mathcal{L} = R_r + \gamma_f \omega^*$ of the rotor resistance R_r and speed ω^* can be on-line identified by stator currents and voltages measurements, with $\gamma_f = \psi^{*2}/T_L$ (see Marino, Scalzi, Tomei, and Verrelli (2013), Marino, Scalzi, Tomei, and Verrelli (2014) and Marino, Tomei, and Verrelli (2010)).

The recent idea in Marino et al. (2014) (see its application to fault-tolerant cruise control problems in Marino, Scalzi et al. (2013)) turns such identifiability and observability issues to its advantage. In other words, when the constant measured speed ω_m^* is used by a suitable adaptive flux observer that provides an exponentially convergent rotor resistance estimate for $\omega_m^* \equiv \omega^*$ (such as the local one in Verrelli, Savoia, Mengoni, Marino, Tomei, and Zarri (2014)), the identifiable linear combination at steady-state becomes

$$\mathcal{L}_e = R_r + \frac{\psi^{*2}}{T_L}(\omega^* - \omega_m^*) \quad \doteq \quad R_{re}.$$

In the presence of speed sensor failures, estimating $\mathcal{L}_e$ (namely, the equivalent rotor resistance R_{re}) 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. In this case, a rotor speed sensor fault may be on-line identified by designing a speed measurement-based adaptive observer and by monitoring the estimate of R_e on the basis of the boundary values R_{rm} and R_{rM} (see Mustafa, Nikolakopoulos, et al. (2016) for similar ideas in a different context). Even partial failures can be thus detected in this way: unlike several model-based fault-detection identification schemes, in which banks of observers are used, a single adaptive observer is simply required.[2] A similar idea has been used in Najafabadi et al. (2011): however, differently from Marino et al. (2014) and Marino, Scalzi et al. (2013), the method is not analytically motivated and the stator resistance is restrictively assumed to be known (with global results being possibly consequently obtained).

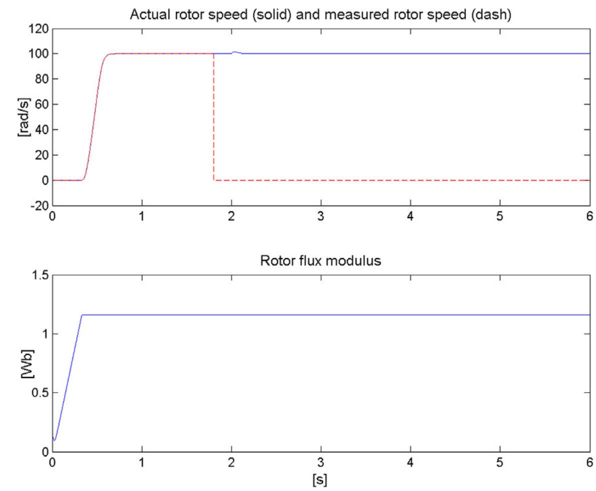

Fig. 1. Rotor speed sensor fault scenario: operating condition.

However, certain relevant experimental evidences concerning the use of such single adaptive observer in the aforementioned context are yet to be theoretically motivated. Such evidences go beyond the already presented analyses and refer to the convergence of the resulting observer estimates under generating operations. In other words, the local nature of the results in Marino et al. (2014) and Marino, Scalzi et al. (2013) requires further investigations, as the motivating example below successfully illustrates (experimental evidences will be reported in Section 5). Take, for instance, the motor in Marino et al. (2014) (rotor resistance $R_r = 3.3\ \Omega$, stator resistance $R_s = 5.3\ \Omega$) to be illustratively controlled to operate, after a short transient, at constant speed ω^* (100 rad/s) and flux modulus ψ^* (1.16 Wb). The load torque T_L, which is positive for $t < 2$ s and negative for $t > 2$ s (recall that in electric vehicle applications, such as the one described in Marino, Scalzi et al. (2013), generator operations may typically occur), is reported in Fig. 1. The adaptive observer in Verrelli et al. (2014) is used. At $t = 1.8$ s the measured speed ω_m abruptly falls to zero (due to a rotor speed sensor fault). The simulation results confirm that, as theoretically expected in Marino et al. (2014) and Marino, Scalzi et al. (2013):

(1) for $t < 1.8$ s (no speed sensor fault under motor operations): $(\omega^* - \omega_m^*) = 0$ and the observer in Verrelli et al. (2014) is prompt to correctly estimate the rotor fluxes and the three critical parameters $(R_{re} \equiv R_r, R_s, T_L)$ (see Figs. 2 and 3 for $t < 1.8$ s);
(2) for $t \in [1.8, 2)$ s (speed sensor fault under motor operations): $(\omega^* - \omega_m^*) > 0$, $R_{re} \neq R_e$ and the observer in Verrelli et al. (2014) is prompt to correctly estimate the rotor fluxes and the three parameters $(R_{re} \neq R_r, R_s, T_L)$ (see Figs. 2 and 3 for $t \in [1.8, 2)$ s), so that the speed sensor fault is successfully detected owing to the fact that R_{re} is apparently out of $[R_{rm}, R_{rM}]$.

However, for $t > 2$ s (speed sensor fault under generating operations), the theoretical expectations of Marino et al. (2014) and Marino, Scalzi et al. (2013) are no longer satisfied: $\hat{\alpha} = \frac{\hat{R}_r}{L_r}$ does not converge to (the now negative) R_{re}/L_r (it actually converges to $-R_{re}/L_r$), whereas $\hat{R}_s$ does not converge to R_s (it actually converges to a large modulus—negative value). Even $\hat{T}_L$ does not converge to (the now negative) T_L (it actually converges to $-T_L$), with the modulus (equal to ψ^*) of the estimated rotor flux vector $\sqrt{\hat{\psi}_{ra}^2 + \hat{\psi}_{rb}^2}$ being surprisingly preserved (see Figs. 2 and 3 for $t > 2$ s).

The new analysis presented in this paper [preliminary results may be found in Verrelli (2013)] provides a definite answer to the above issues,

[2] The above adaptive observer can be even used to detect stator current sensor faults as suggested in Najafabadi, Salmasi, and Jabehdar-Maralani (2011) (see also Aguilera, de la Barrera, De Angelo, and Espinoza Trejo (2016) for the design of a current-sensor fault detection and isolation system for induction motor drives): an index, which is zero when stator currents are correctly estimated by the observer, can be constructed on the basis of the measured and estimated stator currents profiles. In the presence of stator current sensor faults this index cannot be zero and current sensor fault identification can be successfully performed (see the detailed related discussion in Najafabadi et al. (2011)).