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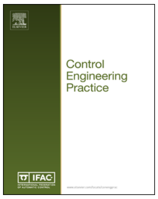

Current-sensor fault detection and isolation for induction-motor drives using a geometric approach

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ABSTRACT

This work presents the design of a current-sensor fault detection and isolation system for induction-motor drives. A differential geometric approach is addressed to determine if faults can be detected and isolated in drives with two line current sensors by using a model based strategy. A set of subsystems is obtained based on the observability co-distribution, whose outputs are decoupled from the load torque (detectability) and only affected by one of the sensors (isolability). A bank of observers is designed for these subsystems in order to obtain residuals for the fault detection and isolation. It is demonstrated that the proposed strategy allows detecting single and multiple sensor faults, including disconnection, offset and gain faults. Experimental results validate the proposal.

1. Introduction

Induction motors (IM) are widely used for servo systems in applications where a high performance speed or torque control is required, such as industry automation and traction systems. Faults in some components of IM drives (IMD) (motor, power electronics, driving circuits, sensors) can degrade the overall system performance, damage its internal components or leave it out of operation. Moreover, in many applications IMD are used in critical systems, where faults can endanger the safety of persons (Aguilera, de la Barrera, & De Angelo, 2012; Giantomassi, Ferracuti, Iarlori, Ippoliti, & Longhi, 2015; Raisemche, Boukhnifer, Larouci, & Diallo, 2014). For this reason, in last years the study of fault detection and isolation systems (FDIS) for IMD has been an important topic in different scientific publications (Arnanz, Miguel, Perán, & Mendoza, 2011; Drobnič, Nemec, Fišer, & Ambrožič, 2012; Mustafa, Nikolakopoulos, Gustafsson, & Kominiak, 2016; Pons-Llinares et al., 2015; Riera-Guasp, Antonino-Daviu, & Capolino, 2015; Zhang, Zhao, Zhou, & Huang, 2014). These systems are used to report the occurrence of a fault and to determine which components are affected, in order to avoid problems caused by faults. In this way, the information provided by the FDIS can be used by a fault tolerant drive (FTD), where a control reconfiguration mechanism enables to keep the IMD in operation despite the fault (Fonod et al., 2015; Marino, Scalzi, Tomei, & Verrelli, 2013; Schuh, Zgorzelski, & Lunze, 2015; Shi & Krishnamurthy, 2014).

In particular, faults in the feedback sensors can produce critical consequences in the IMD performance. As it was shown in Aguilera et al. (2012), a current-sensor fault produces very high current values in the IM phases in a short period of time. Therefore, this fact must be taken into account in order to develop and design the fault detection stage in a FTD for current sensors. Mechanical speed or position sensors are more prone to faults than current sensors. Nevertheless, its effect over phase currents is not so serious, requiring longer times for its detection (Aguilera et al., 2012). In addition, the design of FDIS for mechanical sensors have been widely threated in literature and have proved to give good results (Kommuri, Rath, Veluvolu, Defoort, & Soh, 2015; Raisemche et al., 2014). Therefore, it is necessary to study further the design of fast FDIS for current sensors.

Most fault detection methods for current sensors proposed in literature are based on physical redundancy by using three line current sensors in the IMD (Shi & Krishnamurthy, 2014; Freire et al., 2014; Yu et al., 2014). Nevertheless, the use of redundant sensors increases the system size and costs (Zhang et al., 2013). For this reason, some works propose FDIS using only the information of two line current sensors. For example, in Najafabadi, Salmasi, and Jabehdar-Maralani (2011) an adaptive observer is proposed for

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detecting faults in current, speed or voltage sensors. This technique is based on the assumption that only one sensor may be faulty at a time, namely, only single faults can be isolated. This approach requires to compute the average value of residuals along some electrical cycles, which implies a long time for fault isolation.

A similar method for fault detection and isolation of single sensor faults has been reported in Zhang et al. (2013). The fault detection and isolation is performed by computing residuals from a Kalman filter and the absolute values of the currents. These residuals are not perfectly decoupled from each other, and therefore thresholds must be carefully selected, by following empirical algorithms. This approach is not able to detect the recovery of a sensor from a faulty condition, for example, after a short duration fault.

In Chakraborty and Verma (2015), a FDIS for speed and current-sensor faults based on axes transformations is proposed. Residuals used for the detection of current-sensor faults depend on the reference currents used for the control strategy. These residuals are affected by current tracking errors and faults in the current sensors, therefore it is difficult to distinguish between them when residuals are evaluated. This fact is the main drawback of the cited method. Another drawback is the inability of diagnosing the recovery of a sensor from a fault.

Only disconnection faults were considered in all the previous cited works. In addition, the theoretical analysis for obtaining residuals sensitive to faults in a specific current sensor and decoupled from load variations was not addressed. A comparison of the previous cited FDIS for current sensors is summarized in Table 1.

As it can be seen from cited works, there are few studies on single and multiple current-sensor fault detection and isolation in IMD using only two current sensors. Hence, the main objective of the present work is to propose a method to design a FDIS considering multiple current-sensor faults without physical redundancy. For this purpose, the fundamental problem of residual generation (FPRG) for nonlinear systems is first studied for IMD with current sensors faults (De Persis & Isidori, 2001). This approach proposes geometrical conditions in order to determine if a specific fault can be decoupled from other faults and perturbations. If these conditions are satisfied, then a coordinates transformation can be obtained. This transformation allows to obtain a subsystem whose output is sensitive to that specific fault. If several faults are considered in this analysis, a set of subsystems can be obtained. Then, dedicated residual signals can be designed using a state observer deduced from these subsystems.

The geometric approach was previously applied to IMD addressing different types of faults, such as actuator (Espinoza-Trejo & Campos-Delgado, 2009) and stator short-circuit faults (Khelouat, Benalia, Boukhetala, & Laleg-Kirati, 2012). These works show the usefulness of the approach in order to design diagnostic systems in this application. In this paper, the FPRG is analyzed using a model of the IM considering current sensors faults as arbitrary inputs and the load torque as a perturbation. Based on this model, two new representations of the IM in stationary reference frames are obtained. These representations are used for designing a bank of observers in order to generate dedicated residuals to develop the FDIS.

With the proposed FDIS, the following main technical contributions were achieved (see Table 1):

- Single and multiple current sensor fault detection and isolation are performed without sensor redundancy.
- The FDIS is sensitive to different kind of faults, such as disconnection, offset and gain errors.
- Residuals are sensitive to the fault derivative, allowing an early detection of sudden faults.

Table 1
Comparison of different current-sensor FDIS for IMD.

Reference	Fault detection method	Required measurements[a]	Considered kind of faults	Detection and isolation of single and multiple faults	Independent of the control strategy	Fault detection time	Recovery from a faulty condition
Shi and Krishnamurthy (2014)	Redundant sensor	3 currents	Disconnection	Only detection	Yes	Not reported	Yes
Freire, Estima, and Cardoso (2014)[b]	Redundant sensor	3 currents	Disconnection	Only single faults	Yes	5 ms	Yes
Yu, Wang, Xu, Zhou, and Xu (2014)	Bank of observers	1 voltage, 3 currents, 1 speed	Disconnection	Only single faults	Yes	Not reported	No
Zhang et al. (2013)	EKF	1 voltage, 2 currents, 1 speed	Disconnection	Only single faults	Yes	Not reported	No
Najafabadi et al. (2011)	Adaptive observer	1 voltage, 2 currents, 1 speed	Disconnection	Only single faults	Yes	300 ms	Yes
Chakraborty and Verma (2015)	Analysis of current tracking errors	1 voltage, 2 currents, 1 speed[c]	Disconnection	Yes	No	Not reported	No
This work	Bank of observers	1 voltage, 2 currents, 1 speed	Disconnection, offset, gain	Yes	Yes	1 ms	Yes

[a] Generally, stator voltages are approximated based on the inverter switches command signals and a single DC-link voltage sensor. In some applications, DC-link voltage is assumed to be known and constant, hence the voltage sensor can be avoided (Najafabadi et al., 2011).

[b] This approach was proposed for permanent-magnet synchronous generators, but it could be applicable to IMD. In addition, this approach assumes that measured currents are sinusoidal.

[c] In this proposal, a rotor speed estimation method based on the control reference currents is used when the speed sensor is under fault.