Implicit Fault Tolerant Control: Application to Induction Motors

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Abstract: In this paper we propose an innovative way of dealing with the design of fault tolerant control systems. We show how the nonlinear output regulation theory can be successfully adopted in order to design a regulator able to offset the effect of all the possible faults which can occur and, so doing, also to detect and isolate the occurred fault. The regulator is designed by embedding the (possible nonlinear) internal model of the fault. This idea is then applied to the design of a fault tolerant controller for induction motors in presence of both electrical and mechanical faults. Copyright © IFAC 2002.

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1. INTRODUCTION

Many efforts in the control community have been recently devoted to study “fault tolerant” control (FTC) systems, namely control systems able on one hand to detect incipient faults in sensors and/or actuators and, on the other, to promptly adapt the control law in such a way to preserve pre-specified performances in terms of quality of the production, safety, etc.

The most common approach of dealing with such a problem (see (Frank, 1990) and the reference therein) is to divide the overall design in two distinct phases. The first phase regards the so-called “Fault Detection and Isolation” (FDI) problem which consists of designing a dynamical system (filter) which, processing input/output data, is able to detect the presence of an incipient fault and eventually to precisely isolate it. Once the FDI unit has been designed, the second phase usually amounts in designing a supervisory unit which, on the basis of the information provided by the FDI filter, achieves control reconfiguration to compensate for the effect of the fault and fulfill performances constraints. In general the latter phase is carried out looking for a parameterized controller which is suitable updated by the supervisor according to the information yielded by FDI unit.

It is clear from this brief discussion that the classical approach to FDI and FTC relies upon a “certainty equivalence” idea extensively used in the context of adaptive control, since it involves the explicit estimation of unknown time varying signals/parameters (in the specific case the faults) by the FDI unit and then the explicit reconfiguration of the controller in presence of faults.

The aim of this paper is to follow a different perspective to fault tolerance control. In particular, restricting the analysis to those faults whose side-effects in the system operation are suitably modeled, we look for a controller which embeds an internal model of the fault and hence is able to intrinsically compensate for its effect, regardless its entity and without its explicit...
estimation. In other words the control reconfiguration does not pass through an explicit FDI design but, indeed, is achieved by a proper design of a dynamic controller which is implicitly fault tolerant to all the possible faults whose model is embedded in the regulator.

This idea will be pursued using the theoretical machinery of the (nonlinear) output regulation theory (see (Byrnes et al., 1997)) under the assumption that the side-effect generated by the occurrence of the fault can be modelled as an exogenous signal given by an autonomous “neutrally stable” system (exosystem). As opposite to certainty equivalence-based adaptive control, the distinctive feature of the output regulation theory relies in the design of a regulator which, embedding an internal model of exosystem, is able to offset the effect of any “exosystem-generated” signal without explicitly estimating it. In view of this it is possible to say that the main idea pursued in this paper is exactly that of proposing a fault tolerant control design which is to the classical FDI/FTC approach as the output regulation theory is to certainty equivalence-based adaptive control.

It is interesting to see that, in this framework, the Fault Detection and Isolation phase which is usually the starting point in the design of a Fault Tolerant Control systems, is postponed to that of control reconfiguration since it can be carried out by testing the state of the internal model unit which automatically activates to offset the presence of the fault.

In this paper the approach above outlined is specialized to the design of a fault tolerant control system for Induction Motors (IM). As all the magnetic rotating machines the IM is subject to rotor and stator failures caused by a combination of thermal, electrical, mechanical, magnetic and environmental stresses. Due to these stresses the IM can operate into a failure condition whose effects show with spurious harmonic currents arising in the stator circuit (see (Bellini et al., 2000), (Vas, 1994)) with frequencies which are directly related to the kind of the fault (in general stator or rotor fault) and amplitude and phase which depend on the gravity of the fault.

This allows to see the fault tolerant problem in the perspective above outlined and to cast the problem as an output regulation problem. More in detail we show how an indirect field oriented (IFO) controller (see (Pereyada and Tonielli, 2000), (Ortega et al., 1996) and the reference therein) can be “augmented” with a dynamic unit designed in order to compensate the unknown spurious harmonic currents arising in the stator circuit in presence of rotor or stator faults. In this way a controller which is implicitly fault tolerant to all the faults belonging to the model embedded in the regulator is obtained. With respect to the work presented in (Paoli et al., 2001), where just a semiglobal result was reported, this work presents the more interesting case of the global stabilizer.

The paper is structured as follow. The next section briefly presents the IM model and the global IFO controller able to enforce desired flux and speed profiles when no faults enter into the picture. Section 3 shows how the IM model modifies in presence of stator and rotor faults while section 4 presents the main result of the paper namely the design of a Global Fault Tolerant IFO controller.

2. THE IM MODEL AND THE GLOBAL IFO CONTROLLER

Under assumptions of linear magnetic circuits and balanced operating conditions, the equivalent two-phase model of the symmetrical IM, represented in an arbitrary rotating two-phase reference frame \((d - q)\), is (see (Marino et al., 1993))

\[
\begin{align*}
\dot{x} &= f(x, \omega_0) + Bu + dT_L + bV \\
y &= Cx \\
\epsilon_0 &= \omega_0 \\
\epsilon_0(0) &= 0 \\
\end{align*}
\]

where \(x = (\omega, \Psi_d, \Psi_q, i_d, i_q)^T\) is the space state vector, \(u = (u_d, u_q)^T\) is the control vector and \(y = (\omega, i_d, i_q)^T\) is the vector of measurable variables. The state variables are defined as follows: \(\omega\) is the rotor speed, \((\Psi_d, \Psi_q)\) are rotor flux components, \((i_d, i_q)\) are stator current vector components. The variable \(T_L\) is the unknown load torque and \(V\) represents an exogenous input which is zero in case the IM works in unfaulty mode while is a bounded (unknown) signal in presence of faults (see the treatment in section 3). The variable \(\epsilon_0\) represents the angular position of the rotating \((d - q)\) reference frame with respect to the \(a\)-axis of the fixed stator reference frame \((a - b)\); the relation between the original \((a - b)\) and transformed \((d - q)\) variables is given by

\[
\begin{align*}
x_{dq} &= e^{-j\epsilon_0}x_{ab} \\
x_{ab} &= e^{j\epsilon_0}x_{dq} \\
\end{align*}
\]

where:

\[
e^{-j\epsilon_0} = \begin{bmatrix} \cos \epsilon_0 & -\sin \epsilon_0 \\ \sin \epsilon_0 & \cos \epsilon_0 \end{bmatrix}
\]

where \(x_{yz}\) stands for two-dimensional vectors in the \((y - z)\) reference frame. Vector function \(f(x, \omega_0)\) and constant matrices \(B, d\) and \(b\) are

\[
f(x, \omega_0) = \begin{bmatrix} 
\mu (\Psi_d i_q - \Psi_q i_d) \\
-\alpha \Psi_d + (\omega_0 - \omega) \Psi_q + \alpha L_m i_d \\
- (\omega_0 - \omega) \Psi_d - \alpha \Psi_q + \alpha L_m i_d \\
\alpha \beta \Psi_d + \beta \omega \Psi_q - \gamma i_d + \omega_0 i_q \\
\alpha \beta \omega \Psi_d + \alpha \beta \Psi_q - \omega_0 i_d - \gamma i_q \\
\end{bmatrix}
\]
\[ B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{1}{\sigma} & 0 \\ 0 & \frac{1}{\sigma} \end{bmatrix}, \quad d = \begin{bmatrix} -\frac{1}{J} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad b = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \end{bmatrix} \]

where the positive constants in the model are related to electrical and mechanical parameters of IM as follow

\[ \sigma = L_s \left( 1 - \frac{L_m^2}{L_s L_r} \right), \quad \beta = \frac{L_m}{\sigma L_r}, \quad \mu = \frac{3 L_m}{2 J L_r} \]

\[ \alpha = \frac{R_s}{L_r}, \quad \gamma = \left( \frac{R_s}{\sigma} + \alpha L_m \beta \right) \]

with \( J \) the rotor inertia, \( R_s, R_r, L_m, L_r \) the stator/rotor resistances and inductances respectively, \( L_m \) the magnetizing inductance.

General specifications for speed controlled electric drives regard two IM outputs, namely speed and rotor flux modulus defined as

\[ y_1 = \left[ \frac{\omega}{\sqrt{\Psi_d^2 + \Psi_q^2}} \right] = \left[ \frac{\Psi}{|\Psi|} \right] \]

which are required to follow desired references using the stator voltage vector \( u \) as control inputs and the vector \( y \) as available measures, considering the torque load \( T_L \) as an unknown disturbance. Furthermore steady state flux decoupling, i.e. \( \lim_{t \to \infty} |\Psi_q| = 0 \), is also required.

The tracking problem just formulated has been addressed and solved in several papers (see Ortega et al., 1996), (Peresada and Tonielli, 2000) and the reference therein. In the following the solution denoted by indirect field oriented controller is briefly reviewed. Let \( \omega^* \) and \( \Psi^* \) be denoting the reference signals for the angular velocity and the flux modulus respectively and define the speed-flux modulus tracking errors as

\[ \tilde{\omega} = \omega - \omega^* \quad \tilde{\Psi}_d = \Psi_d - \Psi^* \]

Moreover let the current tracking errors be defined as

\[ \tilde{i}_d = i_d - i_d^* \quad \tilde{i}_q = i_q - i_q^* \]

where

\[ i_d^* = \frac{1}{\alpha L_m} \left[ \alpha \Psi^* + \tilde{\Psi}^* \right] \]
\[ i_q^* = \frac{1}{\mu \Psi^*} \left[ -k_\omega \tilde{\omega} + \tilde{T} + \tilde{\omega}^* \right] \]

with \( k_\omega \), a design parameter and \( \tilde{T} \) an estimate of the load torque \( T_L / J \) whose dynamics are specified later. Moreover define

\[ i_{d1}^* = \frac{1}{\alpha L_m} \left[ \alpha \tilde{\Psi}^* + \tilde{\Psi}^* \right] \]
\[ i_{q1}^* = \frac{1}{\mu \Psi^*} \left[ -k_\omega \tilde{\omega} + \tilde{T} + \tilde{\omega}^* \right] + \left( \tilde{\Psi}^*/\Psi^* \right) i_q^* . \]

Then the following proposition presents the IFO controller yielding global stabilization of the tracking error (see (Peresada and Tonielli, 2000)).

**Proposition 1.** Let \( V(t) \equiv 0 \) and let \( k_\omega, k_{\omega_i}, k_\zeta \) be arbitrary positive constants. There exist positive \( k_{\omega_i}^*, k_q^* \) and \( k_{\omega_i}^* \) such that for all \( k_{\omega_i} \geq k_{\omega_i}^*, k_q \geq k_q^* \) and \( k_{\omega_i} \geq k_{\omega_i}^* \) the state of the closed loop system (1) with control law

\[ \tilde{T} = -k_{\omega_i} \tilde{\omega} \]
\[ \dot{\zeta} = k_\zeta \Psi^* \tilde{\Psi}_q \]
\[ \omega_0 = \omega + s_\omega \]
\[ u_d = u^*_d(k_d) := \sigma \left( -k_{\omega_i} \dot{i}_d + u_d^* \right) \]
\[ u_q = u^*_q(k_q) := \sigma \left( -k_{\omega_i} \dot{i}_q + u_q^* \right) \]

where

\[ s_\omega = \alpha L_m \frac{i_q}{\Psi^*} + \beta \omega \frac{\dot{i}_d}{\Psi^*} \]
\[ u_d^* = -\alpha \beta \Psi^* + \gamma i_d^* - \omega_0 i_q + i_{d1}^* \]
\[ u_q^* = \beta \omega \Psi^* + \gamma i_q^* + \omega_0 i_d + i_{q1}^* + \frac{1}{\Psi^*} (\tilde{\Psi}^*/\Psi^*) i_q^* \]

is bounded for all \( t \geq 0 \) and

\[ \lim_{t \to \infty} \sup \| (\tilde{\omega}(t), \tilde{\Psi}_d(t), \Psi_q(t)) \| = 0 . \]

The previous controller guarantees global asymptotic stability (which indeed can be proved to be exponential) of the tracking error in case \( V \) is identically zero. Note that, as stressed by the notation, the control laws \( u_d^* \) and \( u_q^* \) are parameterized with the current gains \( k_d \) and \( k_q \) which must be chosen sufficiently large. Finally it is worth stressing that, as verified in (Peresada and Tonielli, 2000) with the help of experimental activity, the IFO controller just derived secured a certain degree of robustness with respect to the rotor parameters which are usually characterized by high uncertainties.

### 3. THE IM MODEL IN PRESENCE OF FAULTS

In this section we briefly review how the model of the IM modifies in presence of faults which can be both of mechanical and electrical nature. Following the theory in (Vas, 1994) it turns out that the presence of mechanical and electrical faults generates asymmetry of the IM yielding some slot harmonics.
in the stator winding. In the two-phase model, it is possible to model this effect thinking of a sinusoidal component which corrupts the stator currents, i.e.
\[ i_A \rightarrow i_A + A \sin(\epsilon_c(t) + \phi) \]
\[ i_B \rightarrow i_B + A \cos(\epsilon_c(t) + \phi) , \]
where
\[ \epsilon_c(t) = 2\pi \int_0^t f_e(\tau)d\tau , \]
and \( f_e(\cdot) \) is a function which depends on the specific fault. For example faults caused by rotor asymmetry (due to broken bars or dynamic eccentricity) yields harmonic component at the frequency
\[ f_e = f_{rb} = (1 \pm 2k\sigma_w)f \]
where \( \sigma_w = \omega - \omega_0 \) is the slip, \( f \) is the supply frequency and \( k \) is a positive integer. On the other hand faults generated by stator asymmetry (due, for instance, to short circuit or static eccentricity) generates harmonic components at the frequency
\[ f_e = f_{sec} = f . \]
As far as the amplitude \( A \) and the phase \( \phi \) in (5) are concerned, they depend on the entity of the rotor or stator asymmetry and then can not be considered known since depend on the specific fault severity. Similarly, once the variables are expressed in the \( (d-q) \) reference frame, it turns out that the stator currents in presence of (stator or rotor) asymmetries modify as
\[ i_d \rightarrow i_d + A \sin(\epsilon_e(t) + \epsilon_0(t) + \phi) \]
\[ i_q \rightarrow i_q + A \cos(\epsilon_e(t) + \epsilon_0(t) + \phi) , \]
where \( \epsilon_0 \), introduced in the previous section, denotes the angular position of the \( (d-q) \) reference frame.

Few assumptions are done in the following to simplify relation (9). First of all, for sake of simplicity, we shall concentrate on the case in which the possible frequencies which characterize the sinusoidal additive terms in (9) are constant. This assumption is automatically fulfilled in case the reference angular velocity \( \omega^s \) is constant and, moreover, if a possible fault is allowed to arise just when the steady state has been reached. As a matter of fact, under these assumptions, it is easy to realize that in steady state (bearing in mind (6), (7), (8) and the definition of the slip \( s_w \) in (4))
\[ \epsilon_c(t) + \epsilon_0(t) = 2\pi ft + (\omega^* + s_w^*)t + \epsilon_0^* \]
\[ := \Omega_1 t + \epsilon_0^* \]
(10)
as far as faults concerning stator asymmetries are concerned, and as far as faults concerning rotor asymmetries are concerned. In the previous expressions \( s_w^* \) denotes the (constant) steady state reached by \( s_w \) which turns out to be
\[ s_w^* := \frac{\alpha L_m \hat{T}}{\mu^2 \Omega^2} . \]
while \( \epsilon_0^* \) denotes the (unknown) position of the reference frame once the fault occurs.

As a further hypothesis we assume that the frequencies \( \Omega_1 \) and \( \Omega_{2,\pm k} \) defined in (10) and (11) are perfectly known. This, as clear from the previous computations, amounts to asking perfect knowledge of the IM parameters. Finally, as far as the additive term arising in presence of rotors asymmetry is concerned, we assume that all the terms with frequency characterized by \( k > 1 \) (see (11)) are negligible with respect to the dominant first components with frequencies \( \Omega_{2,\pm 1} \). This allows to model the presence of rotor faults as two harmonics at frequencies respectively \( \Omega_{2,1} \) and \( \Omega_{2,-1} \). However it is worth noting that, by increasing the complexity of the regulator presented in the next section, this assumption can be softened dealing with an arbitrarily large, but finite, value of \( k \).

As a result of this brief discussion, we have that in the setup above presented the presence of faults in the IM shows with harmonic components on the stator currents with known frequency, the latter dependent on the kind of fault which belongs to the two possible classes (rotor or stator faults), and unknown amplitude and phase, the latter depending on the fault severity. In particular it is easy to realize that, defining the exosystem
\[ \dot{w} = Sw \quad w \in \mathbb{R}^6 \]
with
\[ S = \begin{pmatrix} S_s & 0 \\ 0 & S_t \end{pmatrix} \quad S_s = \begin{pmatrix} 0 & \Omega_1 \\ -\Omega_1 & 0 \end{pmatrix} \]
and
\[ S_t = \begin{pmatrix} 0 & \Omega_{2,1} & 0 & 0 \\ -\Omega_{2,1} & 0 & 0 & 0 \\ 0 & 0 & 0 & \Omega_{2,2} \\ 0 & 0 & -\Omega_{2,2} & 0 \end{pmatrix} \]
the additive perturbing terms in (9) can be thought as a suitable combination of the exosystem state, namely
\[ i_d \rightarrow i_d + Q_d w \]
\[ i_q \rightarrow i_q + Q_q w . \]
with
\[ Q_d := \begin{pmatrix} 1 & 0 & 1 & 0 & 1 \end{pmatrix} \]
\[ Q_q := \begin{pmatrix} 0 & 1 & 0 & 1 & 0 \end{pmatrix} . \]
In this way the uncertainty on the amplitude and phase of the additive sinusoidal terms in the faulty condition reflects in that on the initial state of the exosystem.
Recalling the current dynamics in the un-faulty operative condition reported in the previous section, a simple computation shows that, once the perturbing terms \( Q_d w \) and \( Q_q w \) are added, the \((i_d, i_q)\) dynamics modify as

\[
\begin{align*}
\dot{i}_d &= \alpha \beta \Psi_d + \beta \omega i_q - \gamma i_d + \omega_0 i_q + \frac{1}{\sigma} u_d + \\
&\quad -\gamma Q_d w + Q_d S w + \omega_0 Q_q w \\
\dot{i}_q &= -\beta \omega \Psi_q + \alpha \beta \Psi_q - \omega_0 i_q - \gamma i_q + \frac{1}{\sigma} u_q + \\
&\quad -\omega_0 Q_d w - \gamma Q_q w + Q_q S w .
\end{align*}
\]

(14)

In view of this it is readily seen that the model of the IM in presence of faults is given by (1) with the exogenous input \( V \) equal to

\[
V = \left( \begin{array}{c}
-\gamma Q_d w + Q_d S w + \omega_0 Q_q w \\
-\omega_0 Q_d w - \gamma Q_q w + Q_q S w
\end{array} \right).
\]

(15)

or, in a more compact form,

\[
V = \left( \begin{array}{c}
\Gamma_d \\
\Gamma_q
\end{array} \right) w = \Gamma w
\]

where

\[
\Gamma := \left( \begin{array}{cccc}
-\gamma & \ell_1 & -\gamma & \ell_2 \\
-\ell_1 & -\gamma & -\ell_2 & -\gamma & \ell_3 & -\gamma
\end{array} \right)
\]

with

\[
\begin{align*}
\ell_1 &= \omega^* + s_\omega^* + \Omega_1 \\
\ell_2 &= \omega^* + s_\omega^* + \Omega_2, \\
\ell_3 &= \omega^* + s_\omega^* + \Omega_{2,-1}.
\end{align*}
\]

Note that with the above formalism both electrical or mechanical or simultaneous faults are allowed with the first two components of the exosystem state which take into account for stator faults, while the last four for rotor faults.

4. A FAULT TOLERANT GLOBAL IFO CONTROLLER

In the un-faulty mode \( w(t) \) (and hence \( V(t) \)) is identically zero and the IFO controller \((u^*_d, u^*_q)\) presented in proposition 1 meets the design objective of steering the tracking error to zero. On the other hand the presence of some kind of asymmetry, which as above explained is a symptom of incipient fault, reflects in an initial state of the exosystem different from zero which yields a bounded perturbing term \( V(t) \). If the fault (and hence \( w(t) \)) was perfectly known then the control law

\[
\begin{bmatrix}
u_d(t) \\
u_q(t)
\end{bmatrix} = \begin{bmatrix}
u^*_d(t) \\
u^*_q(t)
\end{bmatrix} - \sigma \Gamma w(t)
\]

would achieve fault tolerance by counteracting the exogenous term \( V(t) \). Since the fault is not a priori known we propose a controller, designed adding additional terms to the IFO controller (3), able to asymptotically tackle the exogenous disturbance \( V(t) \) (achieving in this way fault tolerance) and, so doing, also to asymptotically estimate the faults and their gravity. To this end we make use of a well-established theoretical machinery developed in the context of the nonlinear output regulation (see (Byrnes et al., 1997)) by designing an internal model of the exosystem in order to asymptotically reproducing the unknown term \( V(t) \). We show how to design two additional control laws, denoted by \( u^m_d \) and \( u^m_q \), such that choosing the control inputs as

\[
\begin{align*}
u_d &= u^*_d(k_d) + u^m_d \\
u_q &= u^*_q(k_q, k_i) + u^m_q
\end{align*}
\]

(16)

where \( u^*_d(k_d) \) and \( u^*_q(k_q) \) represent the standard global IFO controller (3), then the tracking objective is achieved also in presence of the exogenous fault-generated term \( \Gamma w \). Clearly in (16) the role of \((u^m_d, u^m_q)\) is to compensate for the effects of the faults while \((u^*_d(k_d), u^*_q(k_q, k_i))\) take care of the tracking objective as in the un-faulty operative mode. In order to recover the global result of proposition 1, we design the terms \((u^m_d, u^m_q)\) as saturation functions of the state of the internal model (see the expression (19) below). To this end we shall assume that the exogenous term \( \Gamma w \) is lower and upper bounded by known values and we assume the existence of a \( \lambda_{\text{max}} > 0 \) such that\(^2\)

\[
\|\Gamma w(\cdot)\|_{\infty} \leq \lambda_{\text{max}} .
\]

(17)

Then the following main new result can be proved.

Proposition 2. Let \( \Omega \subset \mathbb{R}^6 \) be an arbitrary compact set such that if \( w(0) \in \Omega \) then (17) holds for some \( \lambda_{\text{max}} \). Moreover let \( F \) and \( G \) be arbitrary \( \mathbb{R}^6 \times \mathbb{R}^6 \) and \( \mathbb{R}^6 \times \mathbb{R}^2 \) matrices such that \( F \) is Hurwitz and \((F, G)\) is a controllable pair and let \( M \) be the unique nonsingular matrix solution of the following Sylvester equation\(^3\)

\[
MS - FM = GT .
\]

(18)

Then fix any \( \lambda \geq \lambda_{\text{max}} \) and consider the control law (16) with

\[
\begin{align*}
u_d^m &= \text{sat}_\lambda(\psi_d M \xi - \psi_d G \bar{T}) \\
u_q^m &= \text{sat}_\lambda(\psi_q M \xi - \psi_q G \bar{T})
\end{align*}
\]

(19)

\(^2\) Note that this assumption amounts to asking that the initial state \( w(0) \) of the exosystem, which is related to the entity of the fault, belongs to an arbitrary large compact set.

\(^3\) Existence and uniqueness of the matrix \( M \) follow from the fact that \( S \) and \( F \) have disjoint spectrum. The fact that \( M \) is nonsingular can be easily proved using observability of the pairs \((S, \Gamma)\) and controllability of the pair \((F, G)\).
where

\[ h(\xi, \bar{I}) = \left( \begin{array}{c} h_d(\xi, \bar{I}) \\ h_q(\xi, \bar{I}) \end{array} \right) := \left( \begin{array}{c} \text{sat}_\alpha(\psi_d M \xi - \psi_d G \bar{I}) - \psi_d M \xi + \psi_d G \bar{I} \\ \text{sat}_\alpha(\psi_q M \xi - \psi_q G \bar{I}) - \psi_q M \xi + \psi_q G \bar{I} \end{array} \right), \]

\[ \psi = \left( \begin{array}{c} \psi_d \\ \psi_q \end{array} \right) := \left( \begin{array}{c} 1_d \\ 1_q \end{array} \right) M^{-1}, \]

\[ K := \left( \begin{array}{cc} k_d & 0 \\ 0 & k_q \end{array} \right), \quad \bar{I} := \left( \begin{array}{c} \bar{I}_d \\ \bar{I}_q \end{array} \right). \]

and \( \text{sat}_\lambda(s) := \text{sgn}(s) \min\{\|s\|, \lambda\} \) is the classical saturation function. Then there exist \( k_{d0}^*, k_{q0}, k_{d0}, M_\xi, \alpha_0, \alpha_\xi \) all positive such that for all \( k_d \geq k_{d0}^*, k_q \geq k_{q0}, k_d \geq k_{d0} \) and for any \((x(0), \xi(0), w(0)) \in \mathbb{R}^5 \times \mathbb{R}^6 \times \Omega\) the state of the closed loop system (1), (13), (15), (16), (19), is bounded and

\[ \| (\bar{\omega}(t), \bar{\Psi}(t), \Psi_q(t)) \| \leq \| (\bar{\omega}(0), \bar{\Psi}(0), \Psi_q(0)) \| M_\xi e^{-\alpha_\xi t} \quad (20) \]

\[ \| (\xi(t) - w(t)) \| \leq \| (\xi(0) - w(0)) \| M_\xi e^{-\alpha_\xi t}. \quad (21) \]

Note that the controller (16)-(19) guarantees fault tolerance, since the tracking specifications are asymptotically (exponentially) fulfilled as claimed in (20), and also fault detection and isolation since the state \( \xi \) of the internal model asymptotically reproduces that of the exosystem (see (21)). The fault detection and isolation phase is carried out testing the state of the internal model unit which automatically compensates for the effect of the fault. In other words the fault is detected and isolated just after its effect has been compensated. This means that the controller just designed is implicitly fault tolerant with respect to the side effects of any fault belonging to the aforementioned classes and no explicit reconfiguration is required. Moreover it is worth stressing that, as the “standard” IFO controller in proposition 1, also this “fault tolerant” modification guarantees global stabilization as far as the state of the IM is concerned. This is achieved recovering the same structure of the IFO controller \((u_d^*, u_q^*)\) in proposition 1 with only the current gains \((k_d, k_q)\) which eventually need to be re-tuned as a consequence of the fault-tolerant modification. This is an important fact since it allows to recover the same performances and robustness of the IFO controller in the unaffected operative mode and moreover to have the design of the global stabilizer which is somewhat independent from that of the FDI and FTC unit.

5. CONCLUSIONS

In this paper we have presented a new idea for dealing with fault tolerant control systems design presenting the design of a fault tolerant control unit for an Induction Motors. We have shown how an Indirect Field Oriented controller processing the currents and the angular velocity of the IM in order to enforce desired flux and speed profiles, can be “enriched” with an internal model of the fault in order to achieve fault tolerance and also fault detection and isolation. The design of the internal model unit can be considered independent from that of the stabilizing IFO unit as only the current gains are eventually required to be re-tuned. We have shown how the internal model unit can be designed in order to have “global” tracking of the desired references and “semi-global” tolerance to possible faults.

6. REFERENCES


