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Fault Tolerant Control based Sliding Mode Application to Induction Motor

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***Abstract*- The aim of this paper is to design and to apply a fault tolerant control approach based sliding mode control strategy to induction motor drives. After giving the induction motor model, we give also the rotor and stator mechanical faults model; in this case the sliding mode (nominal control) present a robustness because it permits to compensate both parametric and load torque disturbance but can't reject the mechanical faults effect. In order to design FTC block an additive control is thus added to the nominal control this additive control illustrated from the internal model which is activated automatically as of appearance of the faults to compensate its effect. Numerical simulations show the effectiveness of the proposed control scheme.**

Keywords- Sliding mode control, robustness, Fault tolerant control, induction motor, mechanical faults model.

I. INTRODUCTION

As automated systems become more complex, a key challenge is how to achieve (at worst) graceful degradation in performance in the event of a fault associated with an actuator, sensor or component subsystem [1]. Under these circumstances, it is important for the system to be kept stable with an acceptable closed loop control performance when faults occur. Ideally, in applications where continuity of operation is a key feature, the closed loop system should be capable of maintaining its pre-specified performance in terms of quality of service, safety, and stability despite the presence of faults [2]. This procedure is rendered possible thanks to the fault tolerant control (FTC) design [3].

Fault tolerance has become an increasingly interesting topic in the last decade where the automation has become more complex. The objective is to give solutions that provide fault accommodation to the most frequent faults and thereby reduce the costs of handling the faults [4].

Induction motors have dominated the field of electromechanical energy conversion, featuring 80% of the motors in use [5]. The applications of induction motors are widespread. Some induction motors are key elements in assuring the continuity of the process and production chains of many industries. A majority of induction motors are used in electric utility industries, mining industries, petrochemical industries, and domestic appliances industries. The list of the industries and applications that induction motors take place in is rather long. IM's are also often used in critical applications such as nuclear plants, aerospace, and military applications, where the reliability must be of high standards [6].

Several failures can affect electrical motor drives [7] and can appear on the level of rotor or stator of induction motor [8]. They can be electric or mechanic. Their causes very varied. Indeed, many studies [9-10] showed that each faults revealed harmonics at specific frequencies in the currents of the machine. This frequential signature dependent on the machine structural parameters [5].

Starting from the work presented in [11] where authors take the FOC as nominal control in the FTC strategy. In [12] author's present the FTC based Backstepping Control. In this paper we take Sliding Mode Control (SMC) as the nominal control which is a robust control scheme based on the concept of changing the controller structure in response to changing the state of the system in order to obtain a desired response. A high speed switching control action is used to switch between different structures and the trajectory of the system is forced to move along a chosen switching manifold in the state space. The behavior of the closed loop system is thus determined by the sliding surface [13].

Our objective in this paper is to design a robust sliding mode control technique to compensate the load torque and the parametric disturbances effect. After giving the rotor and/or stator mechanical faults model in order to design FTC block, we associated the nominal control with an *internal model* which generates an additive term to compensate the faults effect. The level of the compensation is an indicator of the faults severity and the nature of the compensation is a help with the diagnosis.

II. INDUCTION MOTOR MODELING

The setting in the state form of the induction motor model allows the simulation of this latter. The induction motor model in the stator direct and quadrature ($d-q$) reference frame is given by the following state equations:

$$\begin{cases} \dot{x} = f(x) + Bu + DT_L \\ x = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \end{bmatrix}^T = \begin{bmatrix} i_{sd} & i_{sq} & \ddot{\ }_{d} & \Omega \end{bmatrix}^T \\ B = \begin{bmatrix} b & 0 & 0 & 0 \\ 0 & b & 0 & 0 \end{bmatrix}^T \\ D = \begin{bmatrix} 0 & 0 & 0 & d \end{bmatrix}^T \end{cases} \quad (1)$$

With the following expression of field vector *f(x)*:

$$\begin{cases} f_1(x) = a_1 x_1 + \mu_s x_2 + a_2 x_3 \\ f_2(x) = -\mu_s x_1 + a_1 x_2 + a_5 x_3 x_4 \\ f_3(x) = a_8 x_3 + a_{10} x_1 \\ f_4(x) = a_{14} x_2 x_3 \end{cases} \quad (2)$$

$$\mu_s = n_p \Omega + a_7 \frac{x_2}{x_3} \quad (3)$$

The components of this vector are expressed according to the IM parameters as follows:

$$\begin{cases} a_1 = -\left(\frac{1}{T_s \sigma} + \frac{1-\sigma}{T_r \sigma} \right); a_2 = \frac{1-\sigma}{T_r M \sigma} \\ a_5 = -n_p \frac{1-\sigma}{M\sigma}; a_7 = a_{10} = \frac{M}{T_r}; a_8 = -\frac{1}{T_r} \\ a_{14} = \frac{n_p M}{J L_r};\ b = \frac{1}{\sigma L_s}; d = -\frac{1}{j} \end{cases}$$

With: $\pm = 1 - \frac{M^2}{L_r L_s}$, $T_r = \frac{L_r}{R_r}$ et $T_s = \frac{L_s}{R_s}$.

The use of the classical controllers such as the proportional and integral controller (PI) is insufficient to provide good speed tracking performance [14]. To overcome these problems, a robust controller based on the sliding mode principle is proposed for the speed and flux control.

III. SLIDING MODE CONTROL

Sliding Mode Control (SMC) theory, due to its order reduction, disturbance rejection, strong robustness, and simple implementation by means of power converter, is one of the prospective control methodologies for induction motors [15].

In this case the application of sliding mode control strategy to induction motor is divided into two steps. First we take the following equilibrium surface:

$$\begin{cases} S_1 = e_{\cdot\cdot} = x_3^* - x_3 \\ S_2 = e_\Omega = x_4^* - x_4 \end{cases} \text{ and } \begin{cases} S_3 = e_q = x_2^* - x_2 \\ S_4 = e_d = x_1^* - x_1 \end{cases}$$

Where: x_1^*, x_2^*, x_3^* and x_4^* represent respectively the currents, the flux and the speed references.

1. Flux and Speed regulator:

The condition necessary for the system states follow the trajectory defined by the sliding surfaces is $S_i = 0$ which brings back us to define the rotor flux module and speed equivalent control in the following way:

$$\begin{cases} S_1 = 0 \\ S_2 = 0 \end{cases} \Rightarrow \begin{cases} \dot{S}_1 = \dot{x}_3^* - \dot{x}_3 = 0 \\ \dot{S}_2 = \dot{x}_4^* - \dot{x}_4 = 0 \end{cases} \quad (4)$$

In this case we get:

$$\begin{cases} x_1^d = \frac{1}{a_{10}} (\dot{x}_3^* - a_8 x_3) \\ x_2^d = \frac{1}{a_{14} x_3} (\dot{x}_4^* - dT_L) \end{cases} \quad (5)$$

The control law which ensures the attractivity is:

$$\begin{cases} i_{sdn} = -k_1 eval(S_1) \\ i_{sqn} = -k_2 eval(S_2) \end{cases} \quad (6)$$

Where k_1 and k_2 are positive constants. Then from (5) and (6) we get:

$$\begin{cases} x_1^* = x_1^d + i_{sdn} \\ x_2^* = x_2^d + i_{sqn} \end{cases} \quad (7)$$

2. Direct and Quadrature currents regulator:

According to the derivative of the currents surfaces we can generate the tension on the (*d-q*) axis.

$$\begin{cases} \dot{S}_3 = \dot{x}_2^* - \dot{x}_2 = 0 \\ \dot{S}_4 = \dot{x}_1^* - \dot{x}_1 = 0 \end{cases} \quad (8)$$

$$\Rightarrow \begin{cases} u_{2eq} = V_{sqeq} = \frac{1}{b} \left(\dot{x}_2^* - f_2(x) + a_{14} x_3 e_\Omega \right) \\ u_{1eq} = V_{sdeq} = \frac{1}{b} \left(\dot{x}_1^* - f_1(x) + a_{10} e_{\cdot\cdot} \right) \end{cases} \quad (9)$$

Where: $\begin{cases} f_1(x) = a_1 x_1 + \mu_s x_2 + a_2 x_3 \\ f_2(x) = -\mu_s x_1 + a_1 x_2 + a_5 x_3 x_4 \end{cases}$

We ensure the attractive control law by:

$$\begin{cases} V_{sqn} = -k_3 eval(S_3) \\ V_{sdn} = -k_4 eval(S_4) \end{cases} \quad (10)$$

With k_3 and k_4 are positive constants. Finely we get:

$$\begin{cases} u_{2nom} = V_{sq} = V_{sqeq} + V_{sqn} \\ u_{1nom} = V_{sd} = V_{sdeq} + V_{sdn} \end{cases} \quad (11)$$

In this study, the *eval* block usually is any function of the following family: *sign*, *relay* or *linear with saturation*. Both the *sign* and the *relay* functions do not perform accurately in a discrete-time system, resulting in oscillations and undesired chattering. A linear function (*saturation*) with a proper gain provides much better results in reducing oscillations while still maintaining the properties of sliding mode [15].

3. Stability of the closed loop:

The objective is to steer the currents the flux and the speed to their desired references. Let e_d , e_q , $e_{\cdot\cdot}$ and e_Ω be the tracking errors of the currents, the flux and the speed respectively then the dynamic of the tracking errors are given by:

$$\begin{cases} \dot{e}_d = a_1 x_1 + \mu_s x_2 + a_2 x_3 + bV_{sd} - (d(i_{sd})_{ref}/dt) \\ \dot{e}_q = -\mu_s x_1 + a_1 x_2 + a_5 x_3 x_4 + bV_{sq} - (d(i_{sq})_{ref}/dt) \\ \dot{e}_{\cdot\cdot} = a_8 x_3 + a_{10} e_d - \dot{x}_3^* + a_6 (i_{sd})_{ref} \\ \dot{e}_\Omega = a_{14} x_3 e_q + dT_L - \dot{x}_4^* + a_{14} x_3 (i_{sq})_{ref} \end{cases} \quad (12)$$

By taking $k_1 = \frac{k_{\cdot\cdot}}{a_{10}}$ and $k_2 = \frac{k_\Omega}{a_{14} x_3}$ in (6) then (7) will be:

$$(i_{sd})_{ref} = \frac{1}{a_{10}}((\dot{x}_3^* - a_8 x_3) - k_{\cdot\cdot}\, eval\, e_{\cdot\cdot}) \quad (13)$$

$$(i_{sq})_{ref} = \frac{1}{a_{14} x_3}((\dot{x}_4^* + dT_L) - k_\Omega eval\, e_\Omega) \quad (14)$$

From (13) and $\dot{e}_{\cdot\cdot}$ and from (14) and $\dot{e}_\Omega$ we get respectively:

$$\begin{cases} \dot{e}_{\cdot\cdot} = a_{10} e_d - k_{\cdot\cdot}\, eval\, e_{\cdot\cdot} \\ \dot{e}_\Omega = a_{14} x_3 e_q - k_\Omega eval\, e_\Omega \end{cases} \quad (15)$$

By taking $k_3 = \frac{k_q}{b}$ and $k_4 = \frac{k_d}{b}$ in (10) then (11) will be:

$$V_{sq} = \frac{1}{b}(\mu_s x_1 - a_1 x_2 - a_5 x_3 x_4 - a_{14} x_3 e_\Omega + \frac{d(i_{sq})_{ref}}{dt} - k_q eval e_q) \quad (16)$$

$$V_{sd} = \frac{1}{b}(-a_1 x_1 - \mu_s x_2 - a_2 x_3 - a_{10} e_{\cdot\cdot} + \frac{d(i_{sd})_{ref}}{dt} - k_d eval e_d) \quad (17)$$

From (16) and $\dot{e}_q$ and from (17) and $\dot{e}_d$ we get respectively:

$$\begin{cases} \dot{e}_q = -k_q eval\, e_q - a_{14} x_3 e_\Omega \\ \dot{e}_d = -k_d eval\, e_d - a_{10} e_{\cdot\cdot} \end{cases} \quad (18)$$

Consider the following Lyapunov function:

$$V = \frac{1}{2}(e_d^2 + e_q^2 + e_{\cdot\cdot}^2 + e_\Omega^2) \quad (19)$$

The derivative of V with respect to time is:

$$\begin{aligned} \dot{V} &= e_d(-k_d eval e_d - a_{10} e_{\cdot\cdot}) + e_q(-k_q eval e_q - a_{14} x_3 e_\Omega) \\ &+ e_{\cdot\cdot}(a_{10} e_d - k_{\cdot\cdot}\, eval e_{\cdot\cdot}) + e_\Omega(a_{14} x_3 e_q - k_\Omega eval e_\Omega) \end{aligned} \quad (20)$$

We have at $t \to \infty$ $e_i \to 0$ and $eval\, e_i \to 0$ then we take $eval\, e_i = e_i$ where $e_i = e_d, e_q, e_{\cdot\cdot}, e_\Omega$ then the derivative of the Lyapunov function (20) becomes:

$$\dot{V} = -k_d e_d^2 - k_q e_q^2 - k_{\cdot\cdot} e_{\cdot\cdot}^2 - k_\Omega e_\Omega^2 \quad (21)$$

Finely From (21) we see that ($\dot{V} \le 0$) the derivative of the complete Lyapunov function be negative definite this implies that all the error variables are globally uniformly bounded.

IV. DESIGN OF FAULT TOLERANT CONTROL

1. 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. With reference to [11], the faults dealt with in this paper can be summarized in the following two classes:

- Rotor asymmetries, mainly due to broken bars or dynamic eccentricity;
- Stator asymmetries, mainly due to static eccentricity.

Following the theory in [16], it turns out that the presence of stator and rotor faults generates asymmetries in the IM, yielding some slot harmonics (sinusoidal components) in the stator currents (see [11]).

$$\begin{cases} i_{sd} \to i_{sd} + A\sin(\mu_1 t + \ddot{}\,) + \sum_{i=1}^{n_f} [A_i \sin(\mu_{2,i} t + \ddot{}_i) \\ \quad + A_{-i} \sin(\mu_{2,-i} t + \ddot{}_{-i})] \\ i_{sq} \to i_{sq} + A\cos(\mu_1 t + \ddot{}\,) + \sum_{i=1}^{n_f} [A_i \cos(\mu_{2,i} t + \ddot{}_i) \\ \quad + A_{-i} \cos(\mu_{2,-i} t + \ddot{}_{-i})] \end{cases} \quad (22)$$

Where i_{sd} and i_{sq} denote the stator currents in the $(d-q)$ reference frame. The pulsations of the $2n_f + 1$ harmonic components depend on the kind of fault (μ_1 is due to the stator asymmetries,while $\mu_{2\pm i}$, $i = 1, \ldots, n_f$ are due to the rotor asymmetries). The amplitudes $A, A_{\pm i}$ and the phases $\ddot{}$, $\ddot{}_{\pm i}$ are unknown, they depend on the stator or rotor faults entity.

The sinusoidal components generated by the presence of the rotor and stator faults can be modeled by the following exosystem [11]:

$$\dot{w} = S(\acute{}\,) \cdot w \quad w \in \Re^{4n_f + 2} \quad (23)$$

With: $\acute{} = (\mu_1 \quad \mu_{2,1} \quad \mu_{2,-1} \ldots \mu_{2,n_f} \quad \mu_{2,-n_f})$ is the vector of the pulsations.

$$S(\acute{}\,) = \begin{pmatrix} S_s & 0 \\ 0 & S_r \end{pmatrix}$$

$$S_s = \begin{pmatrix} 0 & \mu_1 \\ -\mu_1 & 0 \end{pmatrix} \quad S_r = diag(S_{r,1}, \ \ldots \ S_{r,n_f})$$

$$S_{r,i} = diag\left(\begin{pmatrix} 0 & \mu_{2,i} \\ -\mu_{2,i} & 0 \end{pmatrix}, \begin{pmatrix} 0 & \mu_{2,-i} \\ -\mu_{2,-i} & 0 \end{pmatrix} \right)$$

Where μ_1 is the pulsation of the harmonic generated by the stator faults and $\mu_{2\pm i}, i = 1, \ldots, n_f$ are the pulsations of the harmonics generated by the rotor faults. The amplitudes and the phases of the harmonics are unknown; they depend on the initial state $w(0)$ of the exosystem. Then, the additive sinusoidal terms in (22) can be as a suitable combination of the exosystem state, i.e:

$$\begin{cases} i_{sd} \to i_{sd} + Q_d w \\ i_{sq} \to i_{sq} + Q_q w \end{cases} \quad (24)$$

$$\begin{cases} Q_d = (1 \quad 0 \quad 1 \quad 0 \quad \ldots \quad 1 \quad 0) \\ Q_q = (0 \quad 1 \quad 0 \quad 1 \quad \ldots \quad 0 \quad 1) \end{cases}$$

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, by deriving (24) the $\left(i_d - i_q\right)$ modify as:

$$\begin{cases} \dfrac{di_{sd}}{dt} = \dot{x}_1 = a_1 x_1 + \mu_s x_2 + a_2 x_3 + bu_1 \\ \qquad + a_1 Q_d w + Q_d S w - \mu_s Q_q w \\ \dfrac{di_{sq}}{dt} = \dot{x}_2 = -\mu_s x_1 + a_1 x_2 + a_5 x_3 x_5 + bu_2 \\ \qquad + a_4 Q_q w + Q_q S w + \mu_s Q_d w \end{cases} \tag{25}$$

Bearing in mind the dynamics of the rotor currents in the normal (i.e., in the absence of faults) operative conditions, it is also simple to get the IM dynamics after the occurrence of a fault. As a matter of fact, taking (25) it is readily seen that the IM model in presence of faults is given by (1) and (2) with an exogenous input [17].

$$\begin{cases} \dot{x}_1 = a_1 x_1 + \mu_s x_2 + a_2 x_3 + bu_1 + \Gamma_d w \\ \dot{x}_2 = -\mu_s x_1 + a_1 x_2 + a_5 x_3 x_4 + bu_2 + \Gamma_q w \\ \dot{x}_3 = a_8 x_3 + a_{10} x_1 \\ \dot{x}_4 = a_{14} x_2 x_3 + dT_L \end{cases} \tag{26}$$

With: $V = \begin{pmatrix} \Gamma_d \\ \Gamma_q \end{pmatrix} w \qquad \begin{cases} \Gamma_d = a_1 Q_d + Q_d S - \mu_s Q_q \\ \Gamma_q = a_4 Q_q + Q_q S + \mu_s Q_d \end{cases}$

In this work the pulsations μ_1, $\mu_{2\pm i}$, $i = 1, \ldots, n_f$ are assumed to be unknown. In the presence of faults the IM model becomes:

$$\dot{x} = f(x) + Bu + DT_L + V \tag{27}$$

2. Control reconfiguration

The principal of this FTC system is presented in the fig.1. In this figure the *compensation term* u_c resulting from the equation (30) is known which is useful to compensate the undesirable terms, which makes it possible to give an adequate form to the error dynamics, on the basis of which we calculate the unknown term u_{ad} this *additive control* is added to the *nominal control* and setting to compensate the faults effect (FTC aspect). This additive control results from the internal model whose role is to reproduce the signal representing the faults effect (FDI aspect). The faults effects resulting from a stable autonomous system called *exosystem*.

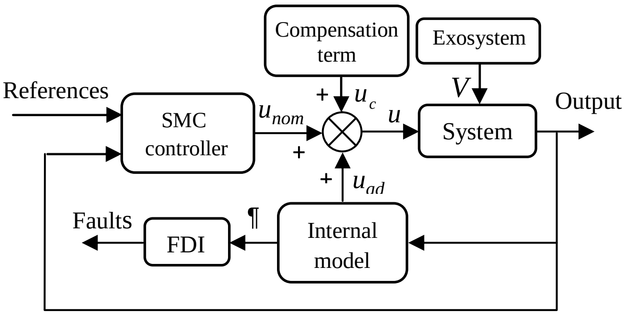

Fig.1 The proposed faults tolerant control structure.

The load torque is compensated by the nominal control. For this (27) becomes:

$$\dot{x} = f(x) + Bu + V \tag{28}$$

The new control law is expressed by:

$$\begin{cases} u = u_{nom} + u_{ad} + u_c \\ u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} u_{1nom} \\ u_{2nom} \end{bmatrix} + \begin{bmatrix} u_{1ad} \\ u_{2ad} \end{bmatrix} + \begin{bmatrix} u_{1c} \\ u_{2c} \end{bmatrix} \end{cases} \tag{29}$$

Where:

$$\begin{cases} u_{1c} = -\dfrac{k_5}{b}(x_1 - x_1^*) - k_4 eval(S_4) \\ u_{2c} = -\dfrac{k_5}{b}(x_2 - x_2^*) - k_3 eval(S_3) \end{cases} \tag{30}$$

On the basis of which we calculate the unknown term u_{ad} with the expression which we retained from (26) and from the nominal control (7) and (11).

The instantaneous difference between the state derivative of the system and the reference becomes:

$$\dot{\bar{x}} = \begin{bmatrix} \dot{\bar{x}}_1 \\ \dot{\bar{x}}_2 \\ \dot{\bar{x}}_3 \\ \dot{\bar{x}}_4 \end{bmatrix} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} - \begin{bmatrix} \dot{x}_1^* \\ \dot{x}_2^* \\ \dot{x}_3^* \\ \dot{x}_4^* \end{bmatrix} = \begin{cases} -k_5 \bar{x}_1 + b_1 u_{1ad} - \Gamma_d w \\ -k_6 \bar{x}_2 + b_2 u_{2ad} - \Gamma_q w \\ a_8 x_3 + a_{10} x_1 - \dot{x}_3^r \\ a_{14} x_2 x_3 - \dot{x}_4^r \end{cases} \tag{31}$$

Let us notice that the first two equations do not depend on the variables $\bar{x}_3$ and $\bar{x}_5$.

- in the third equation if $\bar{x}_1 \to 0 \Rightarrow \bar{x}_3 \to 0$
- in the fourth equation if $\bar{x}_2 \to 0 \Rightarrow \bar{x}_4 \to 0$

In the continuation, for the determination of u_{ad} let us consider the subsystem:

$$\tilde{x} = \begin{bmatrix} \bar{x}_1 \\ \bar{x}_2 \end{bmatrix} \tag{32}$$

Whose dynamics results from the system (31)

$$\begin{cases} \dot{w} = S(\,´\,) \cdot w \\ \dot{\tilde{x}} = \begin{bmatrix} \dot{\tilde{x}}_1 \\ \dot{\tilde{x}}_2 \end{bmatrix} = \begin{cases} -k_5 \bar{x}_1 + b_1 u_{1ad} - \Gamma_d w \\ -k_6 \bar{x}_2 + b_2 u_{2ad} - \Gamma_q w \end{cases} \end{cases} \tag{33}$$

From system (33) we can write it in a matrix form:

$$\dot{\tilde{x}} = H(\tilde{x}) + \tilde{B} \cdot u_{ad} - \Gamma \cdot w \tag{34}$$

$$\begin{cases} H(\tilde{x}) = \tilde{A} \cdot \tilde{x} \ \ and \ \ \tilde{A} = \begin{bmatrix} -k_5 & 0 \\ 0 & -k_6 \end{bmatrix} \\ \tilde{B} = \begin{bmatrix} b & 0 \\ 0 & b \end{bmatrix} \ \ and \ \ \Gamma = \begin{bmatrix} \Gamma_d & 0 \\ 0 & \Gamma_q \end{bmatrix} \end{cases} \tag{35}$$

In this case for the determination of the internal model we introduce a resent implicit fault tolerant control approach which does not rest on the resolution of the Sylvester equation proposed in [11]. The internal model takes then this form [12]:

$$\begin{cases} \dot{¶} = S(´)¶ + N(\tilde{x}) \\ \dim(¶) = \dim(w) = 2n_f \end{cases} \quad (36)$$

Then u_{ad} is chosen like [11]:

$$u_{ad} = \tilde{B}^{-1}\Gamma ¶ \quad (37)$$

Consider the systems (34) and the additive term given by (37) in this case we have:

$$\dot{\tilde{x}} = H(\tilde{x}) + \Gamma \cdot (¶ - w) \quad (38)$$

The new error variable is considered:

$$e = (¶ - w) \quad (39)$$

Its derivative compared to time takes this form:

$$\dot{e} = \dot{¶} - \dot{w} = S(´)¶ + N(\tilde{x}) + S(´)w \quad (40)$$

The equations describing the dynamics of the errors in closed loop are thus:

$$\begin{cases} \dot{\tilde{x}} = \tilde{A} \cdot \tilde{x} + \Gamma \cdot e \\ \dot{e} = S(´)e + N(\tilde{x}) \end{cases} \quad (41)$$

It is necessary to find the expression of $N(\tilde{x})$ which cancels the error of observation of the faults e and makes it possible at the same time to reject their effect for it cancels also $\tilde{x}$.

That is to say the Lyapunov function of the system (41):

$$V = \frac{1}{2}\tilde{x}^T \cdot \tilde{x} + \frac{1}{2}e^T \cdot e \quad (42)$$

After develop of calculates $\dot{V}$ becomes:

$$\dot{V} = \tilde{x}^T \cdot \tilde{A} \cdot \tilde{x} + e^T \cdot \Gamma^T \cdot \tilde{x} + e^T \cdot N(\tilde{x}) \quad (43)$$

In this case the $N(\tilde{x})$ choice is given by:

$$N(\tilde{x}) = -\Gamma^T \tilde{x} \quad (44)$$

Finally $\dot{V}$ is written:

$$\dot{V} = \tilde{x}^T \cdot \tilde{A} \cdot \tilde{x} \le 0 \quad (45)$$

The system (41) becomes:

$$\begin{cases} \Gamma \cdot e = 0 \\ \dot{e} = S(´)e \end{cases} \quad (46)$$

The objective of the control is achieved by adopting the procedure suggested and we able to compensate the faults effect on the system ($x \to 0$) and to reproduce ($e \to 0$) thanks to the internal model.

V. SIMULATION RESULTS

In Fig.2 we start the simulation by a load torque equal to the nominal torque and with a variation of 50% in R_r and R_s, we introduce after that the effect of stator fault at t =0.6 sec.

For Fig.3 we consider the same situation (Fig.2) but in this case we introduce at t=0.6 sec the effect of stator and rotor faults.

From these simulations we can noticed that SMC (nominal control) which we synthesized present a robustness compared

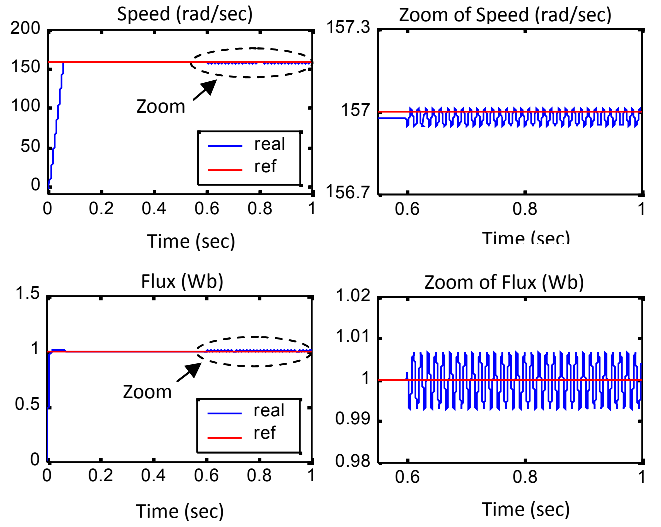

Fig.2 Simulations of the SMC with the presence of stator fault.

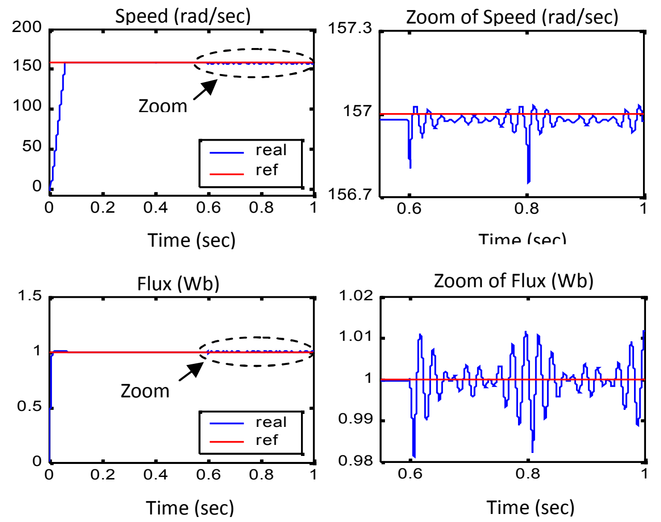

Fig.3 Simulations of the SMC with the presence of stator and rotor faults.

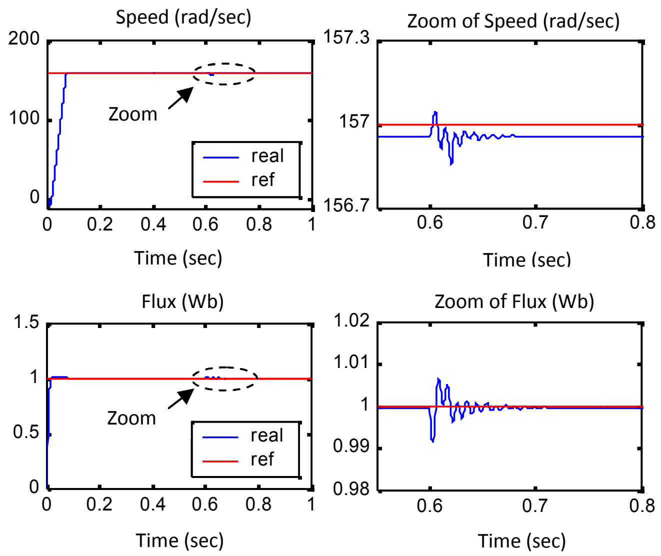

Fig.4 Simulations of the FTC approach (in the presence of stator fault).

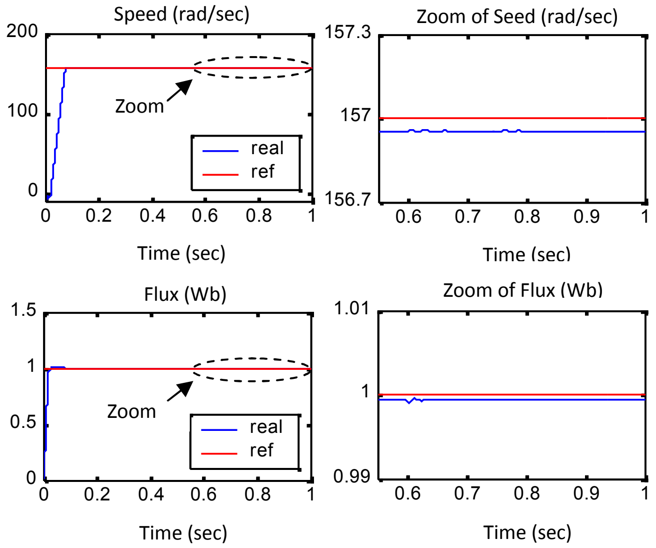

Fig.5 Simulations of the FTC approach (in the presence of stator and rotor faults).

to the parametric and the load torque disturbance, but proves to be insufficient in the event of fault. This is checked by simulations represented above when the *internal model* is not active.

For the Fig.4 and Fig.5 we simulate the global closed loop system with the robust FTC approach. The FTC approach (*when the internal model is active*) which we synthesized rejects the effect of the load torque, the parametric disturbances and also the faults effect.

VI. CONCLUSION

In this paper we present the application of a FTC approach based sliding mode control to induction motors. In un-faulty condition the sliding mode controller permits to steer the flux and the speed variables to their desired references and to reject the parametric and the load torque disturbances, however the presence of rotor and/or stator mechanical faults degraded the performances of the induction motor. In order to compensate the faults effect a robust FTC approach can be designed starting with generating from the internal model state, an additive term wish we add to the *nominal control* (SMC) to compensate the faults effect. The simulation results show the robustness and the effectiveness of the proposed control scheme.

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APPENDIX

RATED DATA OF THE SIMULATED INDUCTION MOTOR

Power =1.08 KW; Voltage=220/380 V; Frequency= 50 Hz

$n_p = 2$; $R_s = 10\,\Omega$; $R_r = 6.3\,\Omega$; $L_s = 0.4642$ H ; $L_s = 0.4612$ H ;

$M = 0.4212$ H ; $J = 0.02$ Kg.m^2 ; f = 0.0005IS