Design of a Fault Tolerant Control Strategy for a class of Induction Motor Drives

H. Mekki[#,*1], O. Benzineb[**2] D. Boukhetala[*3] and M. Tadjine[*4]

[#]*Electrical Engineering Department, University of M'sila.*
B.P 166 Ichbilia M'sila, Algeria.
[1]mekki.hamza@yahoo.fr

[**]*University of Blida Route de Soumaa, Algeria.*
[2]Omar_benzineb@yahoo.fr

[*]*Ecole Nationale Polytechnique (ENP)*
BP 162, Elharrach, Alger, Algeria.
[3]dboukhetala@yahoo.fr
[4]tadjine@yahoo.fr

Abstract- **In this paper the designed fault tolerant control is applied to a class of induction motor drives control characterized by its highly nonlinear and multivariable dynamic system. The proposed approach detects the occurrence of the rotor and stator mechanical fault in the motor and switches itself between a nominal robust control strategy designed for nominal operations and an additive control strategy designed for faulty conditions. The performance of the fault tolerant technique in terms of speed and flux responses was verified using a 1.08 KW induction motor-drive system and the results are presented in this paper.**

Keywords- Robust control, fault tolerant control, induction motor drives, rotor and stator faults.

I. INTRODUCTION

In practical control mechanisms, various system components may be affected by abrupt faults individually or simultaneously during operation. To enhance the reliability and safety of the system, the adverse effects because of the faults require being compensated as soon as possible. The research on diagnosing and accommodating such faults and maintaining acceptable system performance is particularly important for life-critical systems, for example, flight control systems [1].

In recent years, fault-tolerant control (FTC) has begun to concern a wider range of industrial applications such as aerospace, automotive, nuclear power, manufacturing, etc. [2],[3]. Indeed, a significant amount of research on FTC systems was carried out for aircraft flight control system designs [4] and for nuclear power plants [5]. Fault tolerance is no longer limited to high-end systems but also to railway [6] and automobile applications [7]. It becomes an important means to increase the reliability, availability, and continuous operation of electromechanical systems among the automotive ones [8].

Remarkable progress has been made in the area of failure accommodation control with various effective design methods. In general, the FTC approaches can be classified into two types as presented in [1]: the passive approach and the active approach. In the passive approach, the controller is designed to maintain acceptable performances against a set of faults without any change in the control law. In the active approach, first the faults are detected and isolated (fault detection and isolation step), second the control law is changed (control reconfiguration step) to maintain specific performances [9]. This paper is concerned with the passive FTC.

Induction motors have dominated the field of electromechanical energy conversion, featuring 80% of the motors in use [10]. The applications of IM's 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 [11].

Induction Motors (IM) are subjected to various faults, such as stator short circuits, broken bars or rings, eccentricity, sensor and actuator faults,...etc. As in ([12], [13]), this paper is concerned with the rotor asymmetries caused by broken bars or dynamic eccentricity and stator asymmetries caused by static eccentricity. The presence of rotor and stator asymmetries induces harmonic components in the stator currents with frequencies which are directly related to the kind of the fault (stator or rotor fault) and amplitude and phase which depend on the severity of the fault ([12], [13]).

There are many literatures concerning fault tolerant control of induction motors ([14], [15]). This paper focuses on the implicit fault tolerant controller proposed in ([12], [13]), where the effects generated by the occurrence of the fault are

assumed to be modeled as an exogenous signal given by an autonomous" neutrally stable" system. Indeed, many studies [16], [17] showed that each faults revealed harmonics at specific frequencies in the currents of the machine.

Starting from the work presented in [13] where authors take the FOC as nominal control in the FTC strategy. In [18], [19] author's present the FTC based Backstepping Control. In this paper we take Variable Structure Control (VSC) 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 [20].

In this paper, a FTC system is designed to compensate adverse effects of mechanical faults on the level of IM performance. In the proposed strategy, the first a Variable Structure controller as nominal controller is employed to achieve control objectives (reference rotor flux and speed tracking) when IM is fault-free. Then we associated the nominal control with an *internal model* which generates an additive term to compensate the rotor and/or stator mechanical faults effect.

This paper is organized as follows: Section 2 describes the IM oriented model. Section 3 is devoted to the design of the Variable Structure controller which is able to steer the flux and speed variables to their desired references. In Section 4, modeling method of mechanical faults is described for IM drives. In Section 5, a FTC system is surveyed. In Section 6, the simulation results are presented. Section 7 gives some concluding remarks on the proposed fault tolerant controller.

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:

$$\begin{cases} \dot{x} = f(x) + Bu + DT_L \\ x = \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \end{bmatrix}^T = \begin{bmatrix} i_{sd} & i_{sq} & \{_d & \Omega \end{bmatrix}^T \end{cases} \quad (1)$$

Where: $B = \begin{bmatrix} b & 0 & 0 & 0 \\ 0 & b & 0 & 0 \end{bmatrix}^T$ and $D = \begin{bmatrix} 0 & 0 & 0 & d \end{bmatrix}^T$

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

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

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

Where the components of this vector are expressed according to the induction motor parameters as follows:

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

With: $\dagger = 1 - \frac{M^2}{L_r L_s}$, $T_r = \frac{L_r}{R_r}$ 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 [21]. To overcome these problems, a robust controller based on the variable structure principle is proposed for the speed and flux control.

III. VARIABLE STRUCTRE CONTROL

Control (VSC) or sliding mode control (SMC) is one of the effective nonlinear robust control approaches since it provides system dynamics with an invariance property to uncertainties once the system dynamics are controlled in the sliding mode.

The first step of SMC design is to select a sliding surface that models the desired closed-loop performance in state variable space. Then the control should be designed such that system state trajectories are forced toward the sliding surface and stay on it [22].

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:

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

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 $S_i = 0$ (*i=1,..., 3*) which brings back us to define the rotor flux module and speed equivalent control from the derivative of the two first surfaces in the following way:

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

The virtual control law in this case is given by:

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

The control law which ensures the attractivity is given by:

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

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

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

2. Direct and Quadrature currents regulator:

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

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

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

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

We ensure the attractive control law by:

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

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

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

In this study, the *eval* block usually is any function of the following family: *sign*, *relay* or *linear with saturation* as presented in fig. 1. 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 [23].

The *eval* function is implemented in this case as a linear gain with saturation [24]:

a)   b)   c)

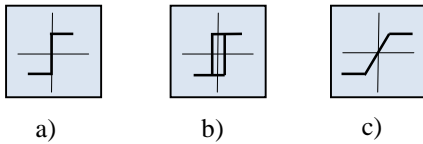Fig. 1. Typical *eval* function (a) *SIGN*   (b) *RELAY*
(c) *LINEAR WITH SATURATION*

$$eval(x) = \begin{cases} x.k_{eval} & \text{if lower limit} < x < \text{upper limit} \\ \text{upper limit} & \text{if } x > \text{upper limit} \\ \text{lower limit} & \text{if } x < \text{lower limit} \end{cases}$$

where k_{eval} is a constant related to the system dynamics.

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, $e_\{$ 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:

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

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

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

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

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

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

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

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

$$V_{sd} = \frac{1}{b}(-a_1 x_1 - \check{S}_s x_2 - a_2 x_3 - a_{10}e_\{ + \frac{d(i_{sd})_{ref}}{dt} - k_d eval\, e_d) \tag{17}$$

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

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

Consider the following Lyapunov function:

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

The derivative of V with respect to time is:

$$\dot{V} = e_d(-k_d eval\, e_d - a_{10}e_\{) + e_q(-k_q eval\, e_q - a_{14}x_3 e_\Omega) + e_\{(a_{10}e_d - k_\{ eval\, e_\{) + e_\Omega(a_{14}x_3 e_q - k_\Omega eval\, e_\Omega) \tag{20}$$

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 $e_i = e_d, e_q, e_\xi, e_\Omega$ then the derivative of the Lyapunov function (20) becomes:

$$\dot{V} = -k_d e_d^2 - k_q e_q^2 - k_\xi e_\xi^2 - k_\Omega e_\Omega^2 \tag{21}$$

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 errors variables are globally uniformly bounded.

IV. 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 [13], 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 [25], 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 [13]).

$$
\begin{cases}
i_{sd} \to i_{sd} + A\sin(\check{S}_1 t + \{\,) + \sum_{i=1}^{n_f}[A_i \sin(\check{S}_{2,i} t + \{_i) \\
\qquad + A_{-i} \sin(\check{S}_{2,-i} t + \{_{-i})] \\
i_{sq} \to i_{sq} + A\cos(\check{S}_1 t + \{\,) + \sum_{i=1}^{n_f}[A_i \cos(\check{S}_{2,i} t + \{_i) \\
\qquad + A_{-i} \cos(\check{S}_{2,-i} t + \{_{-i})]
\end{cases} \tag{22}
$$

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 ($\check{S}_1$ is due to the stator asymmetries, while $\check{S}_{2\pm i}$, $i = 1,\ldots,n_f$ are due to the rotor asymmetries). The amplitudes A, $A_{\pm i}$ and the phases $\{$, $\{_{\pm i}$ 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 [13]:

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

With: $‰ = (\check{S}_1 \quad \check{S}_{2,1} \quad \check{S}_{2,-1} \ldots \check{S}_{2,n_f} \quad \check{S}_{2,-n_f})$ is the vector of the pulsations.

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

$$S_s = \begin{pmatrix} 0 & \check{S}_1 \\ -\check{S}_1 & 0 \end{pmatrix} \quad S_r = diag(S_{r,1}, \ldots S_{r,n_f})$$

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

Where $\check{S}_1$ is the pulsation of the harmonic generated by the stator faults and $\check{S}_{2\pm i}$, $i = 1,\ldots,n_f$ are the pulsations of the harmonics generated by the rotor faults. Then, the additive sinusoidal terms in (22) can be as a suitable combination of the exosystem state, i.e:

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

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 ($i_d - i_q$) modify as:

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

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

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 [18].

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

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

In this work the pulsations $\check{S}_1, \check{S}_{2\pm i}, i = 1,\ldots,n_f$ are assumed to be unknown. In the presence of faults the IM model becomes:

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

V. FAULT TOLERANT CONTROL STRATEGY

The principal of this FTC system is presented in this section (See Fig. 2). In this case 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*.
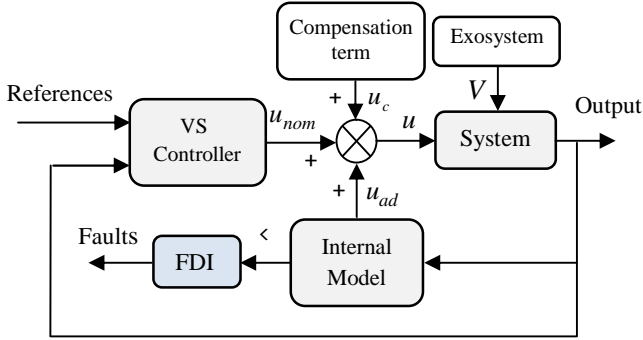

Fig.2 The proposed faults tolerant control structure.

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:

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

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)

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

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

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

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

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 [13]. The internal model takes then this form as presented in [19]:

$$\begin{cases} \dot{\varsigma} = S(\omega)\varsigma + N(\tilde{x}) \\ \dim(\varsigma) = \dim(w) = 2n_f \end{cases} \tag{36}$$

Then u_{ad} is chosen like [13]:

$$u_{ad} = \tilde{B}^{-1} \Gamma \varsigma \tag{37}$$

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

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

The new error variable is considered:

$$e = (\varsigma - w) \tag{39}$$

Its derivative compared to time takes this form:

$$\dot{e} = \dot{\varsigma} - \dot{w} = S(\omega)\varsigma + N(\tilde{x}) + S(\omega)w \tag{40}$$

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

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

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):

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

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

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

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

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

Finally the Lyapunov derivative function $\dot{V}$ is written:

$$\dot{V} = \tilde{x}^T \cdot \tilde{A} \cdot \tilde{x} \leq 0 \tag{45}$$

The system (41) becomes:

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

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.

VI. SIMULATION RESULTS

The parameters of the simulated IM are given in Tab. 1. In Fig.3 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.4 we consider the same situation but in this case we introduce at t=0.6 sec the effect of stator and rotor faults.

Tab. 1 RATED DATA OF THE SIMULATED INDUCTION MOTOR

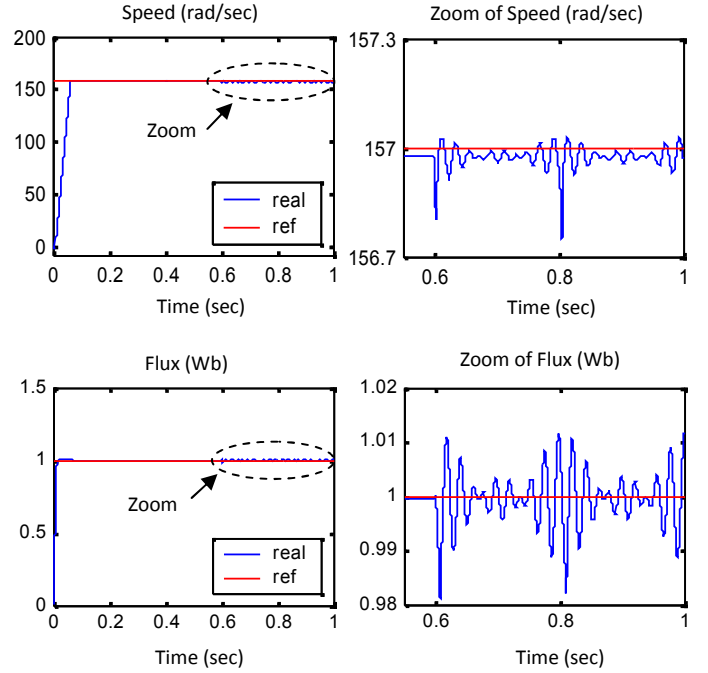| Rated Values		Power	1.08	KW
		Voltage	220/380	V
		Frequency	50	Hz
		n_p	2	
Rated parameters		R_s	10	Ω
		R_r	6.3	Ω
		L_s	0.4642	H
		L_r	0.4612	H
		M	0.4212	H
		J	0.02	Kg.m^2
		f	0.005	IS

Fig.4 Simulations of the VSC in the presence of stator and rotor fault.
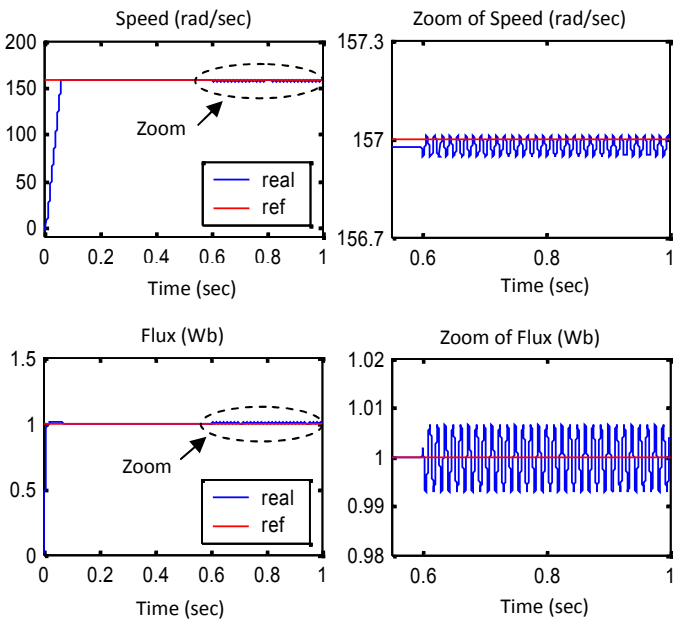

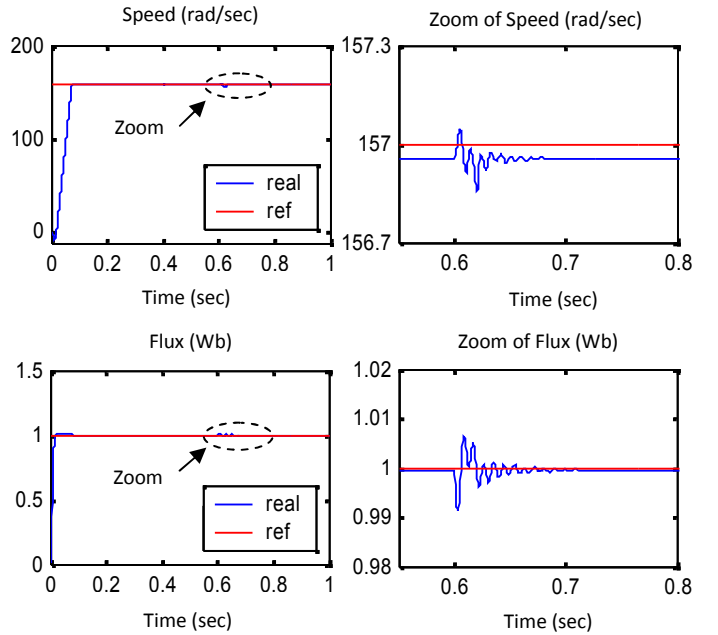Fig.3 Simulations of the VSC in the presence of stator fault.

Fig.5 Simulations of the FTC approach (in the presence of stator fault).

From these simulations (Fig. 3 and Fig. 4) we can noticed that VSC (nominal control) which we synthesized present a robustness compared 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.5 and Fig.6 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.
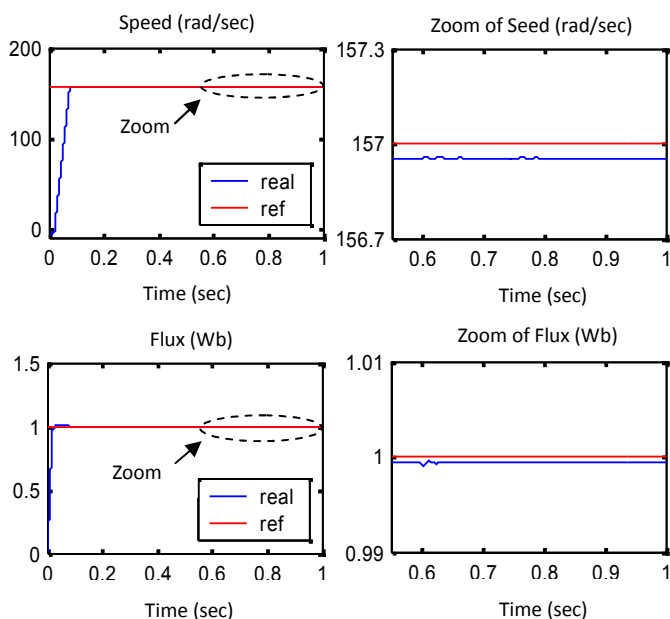

Fig.6 Simulations of the FTC approach (in the presence of stator and rotor faults).

VII. CONCLUSION

In this paper, great effort was made to clarify that variable structure controller is able to meet control objectives only when no mechanical fault occurs in IM (in un-faulty condition) but after having mechanical faults happened, its performance is weakened which increases rotor flux and speed errors. In order to compensate the effect of rotor and/or stator mechanical faults and to design a FTC approach, an additive control signals generated from the internal model were applied. This operation resulted in improvement of control strategy so that rotor speed and flux track its reference values even when mechanical faults took place.

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