Fault Tolerant Control of PMSM Drive Using Sliding Mode Strategy

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***Abstract*— In this study, a Fault Tolerant Control (FTC) based Sliding Mode Control (SMC) strategy has been proposed to improve control performance of Permanent Magnet Synchronous Motor (PMSM) drive. The proposed SMC has proved its effectiveness through the different studies. The advantage that makes such an important approach is its robustness versus the parametric and the load torque disturbances. However, this approach implies a disadvantage under actuator faults. Indeed, the faults dealt with in this paper can be summarized in the class of stator asymmetries, mainly due to static eccentricity. In order to deal with this later and to solve this problem a FTC approach has been developed. Moreover, stability of the closed-loop system is guaranteed in the sense of Lyapunov stability theorem. Results of numerical simulations state that the proposed controller is successful in achieving high PMSM currents and speed tracings performances in the presence of load torque disturbances and actuator failures.**

Keywords*— Fault tolerant control, Lyapunov stability, PMSM, Sliding mode control, Stator asymmetries fault.

I. Introduction

Permanent magnet synchronous motor (PMSM) speed control, with high precision and high torque performances, is of a great importance to monitor productivity. The most conventional used controller is the proportional and integral (PI), since its synthesis is based on simple and well known automatic control methods. However, the unmodelled dynamics, the eventual mistakes and the strong nonlinearity make the PI speed controller unable to deal with all those difficulties [1]. To overcome the above problems, many robust control strategies have been proposed in the literature.

In fact, sliding mode control (SMC) theory was over-looked because of the development in the famous linear control theory, during the last 20 years it has shown to be a very effective control method [2]. SMC have been successfully used in many control applications, especially for electromechanical systems [3] and for PMSM [4-6].

In the last years, a novel SMC with an integral switching surface has attracted a lot of attentions and offer more advantage compared to the conventional SMC (see [7-8]). Successively, many application examples of this control strategy have been developed in the literature and different class of systems are studied. Hence, in [7] and [8] electropneumatic servodrive and electromechanical systems are considered respectively. Indeed, the experimental results verify that the SMC with integral surface provides favorable tracking performance, faster and smoother speed regulation with regard to parameter variations and disturbances compared with the results obtained from conventional SMC controllers. Despite these advantages, the events of a fault associated with an actuator, sensor or component subsystem achieve (at worst) graceful degradation in the system performance. To overcome these problems, the fault tolerant control (FTC) idea has been developed.

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 [9]. Indeed, the survey papers [10] and [11] review the concepts and the state of the art in the field of FTCs.

There are many literatures concerning FTC of PMSM ([9], [12-13]) and induction motor [14]. Indeed, the presence of faults generates asymmetries in the PMSM, yielding some slot harmonics (sinusoidal components) in the stator currents (see [15] and [16]). Indeed, in [9] the design of a FTC for PMSM is based on observers. Author's present in [12] a FTC based Direct Torque Control for PMSM. In [13] a complex internal model based FTC strategy for PMSM is presented. That paper focus of the combination between complex internal model (need compensation term u_c) and Backstepping controller. Compared to the existing results this paper offer more advantage especially in term of robustness and efficiency.

Starting from the new recent approaches ([17]-[20]) dealing with faults based sliding mode method to enhance the robustness of FTCs. Indeed, the problem of FTC design on SMC schemes is still in its early stage of development, and a few results have been reported in the literature [19]. In the current paper, we investigate the use of SMC augmented by integral switching surface which is able to steer the current and the speed variables to their desired references and presents a remarkable robustness under parametric and load torque disturbances. This later is combined with simple internal model (don't need u_c term) in order to design a FTC of PMSM.

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II. PMSM HEALTHY MODEL

The PMSM healthy model in the rotor direct and quadrature rotating ($d-q$) reference frame is given by the following state equations [9], [13]:

$$\begin{cases} \dot{x} = f(x) + Bu + DT_L \\ x = (x_1 \quad x_2 \quad x_3)^T = (i_d \quad i_q \quad \omega_r)^T \\ u = \begin{pmatrix} u_d = V_{sd} \\ u_q = V_{sq} \end{pmatrix};\ B = \begin{pmatrix} b_1 & 0 & 0 \\ 0 & b_2 & 0 \end{pmatrix}^T \\ D = (0 \quad 0 \quad d)^T \end{cases} \quad (1)$$

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

$$\begin{cases} f_1(x) = a_1 x_1 + a_2 x_2 x_3 \\ f_2(x) = a_3 x_2 + a_4 x_3 + a_5 x_1 x_3 \\ f_3(x) = a_6 x_2 + a_7 x_3 + a_8 x_1 x_2 \end{cases} \quad (2)$$

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

$$\begin{pmatrix} a_1 = -\frac{R_s}{L_d}; a_2 = \frac{L_q}{L_d}; a_3 = -\frac{R_s}{L_q}; a_4 = -\frac{\varphi_f}{L_d}; a_5 = \frac{L_d}{L_q}; a_6 = -\frac{n_p^2 \varphi_f}{J} \\ a_7 = -\frac{f}{J};\ a_8 = \frac{n_p^2 \varphi_f}{J}(L_d - L_q); d = -\frac{n_p}{J};\ b_1 = \frac{1}{L_d}; b_2 = -\frac{1}{L_q} \end{pmatrix}$$

As presented in the appendix we take in this paper in PMSM with smooth poles $L_d = L_q = L$ then $(a_8 = 0)$.

The use of the classical controllers such as the proportional and integral controller (PI) is insufficient to provide good speed tracking performance. To overcome these problems, a robust controller based sliding mode control with integral switching surfaces is proposed.

III. SLIDING MODE CONTROL STRATEGY

SMC is a kind of robust control technique that can deal with large uncertainty with discontinuous control strategy. It is an effective way of designing control system with features of reduced order synthesization and invariance to dynamic uncertainties and external perturbations ([2], [20]). The insensitivity and robustness of SMC make it suitable for handling system under control with satisfactory performance in both normal and faulty operating conditions [18].

As presented in [7-8], the SMC with an integral surface gives more useful results at all the operating points (central position and extremity). The static error has been decreased enough relative to the other controller and the dynamics is satisfactory especially at the extremity.

In this work, using the reduced nonlinear PMSM model in (1), it is possible to design speed and currents SM controller (see figure 1). Then, three sliding surfaces with integral action are used and taken as follows:

$$\begin{pmatrix} S_1 = x_3 - x_3^* + m_1 \int (x_3 - x_3^*) dt \\ S_2 = x_2 - x_2^* + m_2 \int (x_2 - x_2^*) dt \\ S_3 = x_1 - x_1^* + m_3 \int (x_1 - x_1^*) dt \end{pmatrix}$$

($x_3^* = \omega_r^*$), ($x_2^* = i_q^*$) and ($x_1^* = i_d^*$) represents the speed and currents references. m_1, m_2 and m_3 are positive constants.

1. Speed regulator:

The condition necessary for the system states follow the trajectory defined by the sliding surfaces is $S_1 = 0$ which brings back us to define the speed equivalent control in the following way:

$$S_1 = 0 \Rightarrow \dot{S}_1 = (\dot{x}_3 - \dot{x}_3^*) + m_1 (x_3 - x_3^*) = 0 \quad (3)$$

In this case we get: In this case the equivalent quadratic current references are given by:

$$x_2^{eq} = \frac{1}{a_6}(-a_7 x_3 - dT_L + \dot{x}_3^* - m_1 (x_3 - x_3^*)) \quad (4)$$

The control law which ensures the attractiveness is given by:

$$x_2^n = -k_1 sign(S_1) \quad (5)$$

k_1 is positive constant. By addition between the equivalent control x_2^{eq} and the switching control x_2^n illustrated from (4) and (5) we get the first sliding mode controller:

$$x_2^* = \frac{1}{a_6}(-a_7 x_3 - dT_L + \dot{x}_3^* - m_1 (x_3 - x_3^*)) - k_1 sign(S_1) \quad (6)$$

2. Direct and Quadrature currents regulator:

In this case the condition necessary for the system states follow the trajectory defined by the sliding surfaces is $S_2 = 0$ and $S_3 = 0$ which brings back us to define the direct and quadratic currents equivalents control in the following way:

$$\begin{cases} S_2 = 0 \\ S_3 = 0 \end{cases} \Rightarrow \begin{cases} \dot{S}_2 = (\dot{x}_2 - \dot{x}_2^*) + m_2 (x_2 - x_2^*) = 0 \\ \dot{S}_3 = (\dot{x}_1 - \dot{x}_1^*) + m_3 (x_1 - x_1^*) = 0 \end{cases} \quad (7)$$

According to the derivative of the direct and quadratic currents surfaces we can generate the tension given as fellow:

$$\begin{cases} u_q^{eq} = V_{sq}^{eq} = \frac{1}{b}\left(\dot{x}_2^* - a_3 x_2 - a_4 x_3 - a_5 x_1 x_3 - m_2 (x_2 - x_2^*)\right) \\ u_d^{eq} = V_{sd}^{eq} = \frac{1}{b}\left(\dot{x}_1^* - a_1 x_1 - a_2 x_2 x_3 - m_3 (x_1 - x_1^*)\right) \end{cases} \quad (8)$$

The attractive control law is ensured and given by:

$$\begin{cases} V_{sq}^n = -k_2 sign(S_2) \\ V_{sd}^n = -k_3 sign(S_3) \end{cases} \quad (9)$$

With k_2 and k_3 are positive constants. Finely, from (8) and (9) we get the global sliding mode controllers:

$$\begin{cases} u_q^{nom} = \frac{1}{b}\left(\dot{x}_2^* - a_3x_2 - a_4x_3 - a_5x_1x_3 - m_2(x_2 - x_2^*)\right) \\ \qquad - k_2 sign\,(S_2) \\ u_d^{nom} = \frac{1}{b}\left(\dot{x}_1^* - a_1x_1 - a_2x_2x_3 - m_3(x_1 - x_1^*)\right) - k_3 sign\,(S_3) \end{cases} \quad (10)$$

<u>*Remark 1:*</u> The algorithm structure of the currents and speed sliding mode augmented by integral switching surface control (SMC) of PMSM has been described in detail in Figure 1.

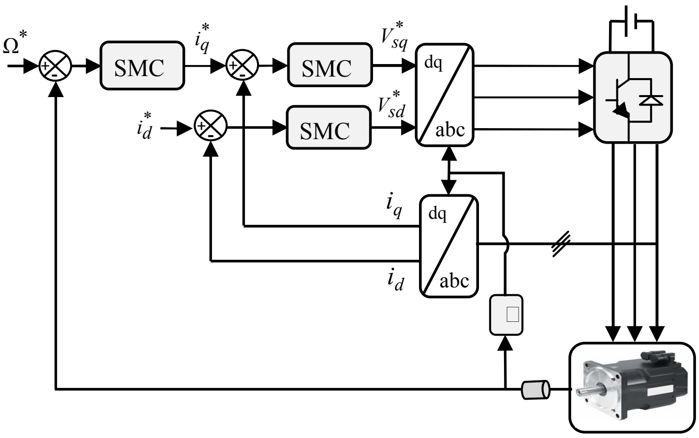

Fig.1. Block diagram of the proposed control scheme.

3. Closed loop stability analysis:

The control objective in this case is to force the PMSM speed to follow its reference ($\omega_r \to x_3^*$) and maintain in the same time the direct current to zero ($i_d \to 0$) under load torque disturbance. Let e_d, e_q and e_ω be the tracking errors of the currents and the speed then the dynamic of the tracking errors are given by:

$$\begin{cases} \dot{e}_d = a_1x_1 + a_2x_2x_3 + b_1V_{sd} - \dot{x}_1^* \\ \dot{e}_q = a_3x_2 + a_4x_3 + a_5x_1x_3 + b_2V_{sq} - \dot{x}_2^* \\ \dot{e}_\omega = a_6x_2 + a_7x_3 + dT_L - \dot{x}_3^* \end{cases} \quad (11)$$

By taking $k_1 = \frac{k_\omega}{a_6}$ in (6), from this equation and $\dot{e}_\omega$ given in (11) we get:

$$\dot{e}_\omega = -k_\omega sign\,(S_1) - m_1 e_\omega \quad (12)$$

By taking $k_2 = \frac{k_q}{b_2}$ and $k_3 = \frac{k_d}{b_1}$ in (10) from this new equation, $\dot{e}_q$ and $\dot{e}_d$ given in (11) we get:

$$\begin{cases} \dot{e}_q = -k_q sign\,(S_2) - m_2 e_q \\ \dot{e}_d = -k_d sign\,(S_3) - m_3 e_d \end{cases} \quad (13)$$

Consider the following Lyapunov function:

$$V = \frac{1}{2}e_d^2 + \frac{1}{2}e_q^2 + \frac{1}{2}e_\omega^2 \quad (14)$$

The derivative of V with respect to time is:

$$\dot{V} = e_d(-k_d sign\,(S_3) - m_3 e_d) + e_q(-k_q sign\,(S_2) - m_2 e_q) + e_\omega(-k_\omega sign\,(S_1) - m_1 e_\omega) \quad (15)$$

To assure the stability m_i $(i = 1,\ldots,3)$ must chosen's as follows:

$$\begin{cases} m_1 >> \left|k_\omega sign\,(S_1)\right|_{\max} ;\ m_2 >> \left|k_q sign\,(S_2)\right|_{\max} \\ m_3 >> \left|k_d sign\,(S_3)\right|_{\max} \end{cases}$$

Then the derivative of the Lyapunov function (15) becomes:

$$\dot{V} < -m_3e_d^2 - m_2e_q^2 - m_1e_\omega^2 \quad (16)$$

Finely From (16) it's shown that ($\dot{V} \le 0$) the derivative of the complete Lyapunov function be negative definite this implies that the error variables e_d, e_q and e_Ω are globally uniformly bounded and maintain the system closed loop performance in presence of load torque disturbances.

<u>*Remark 2:*</u> The *sign* function does not perform accurately in a discrete-time system, resulting undesired chattering. A linear function with a proper gain (*sat*) provides much better results in reducing oscillations while still maintaining the properties of sliding mode (see [3]). In this paper the *sign* function is approximated by a saturation (*sat*) function.

IV. Design of Fault Tolerant Control

1. PMSM faulty model

In this section we briefly review how the PMSM model will be modifies in presence of faults. The faults dealt with in this paper can be summarized in the class of stator asymmetries, mainly due to static eccentricity as presented in [15] and [16]. Indeed, in [15] the amplitude of side-band components at frequencies *(1± (2k-1)/P) fs*, where *k* is an integer number, has been employed for static eccentricity diagnosis in PMSMs. Despite, the PMSMs under eccentricity fault have been investigated in a few papers (see [15-16]) and performance of the faulty motor has been analyzed, no criterion has been so far recommended for eccentricity fault diagnosis.

The sinusoidal components generated by the stator faults can be modeled by the following exosystem [13-14]:

$$\dot{w} = \delta(\omega_s) \cdot w \quad (17)$$

With: $w \in \Re^{2n_f}$ and $\delta(\omega_s)$ is the vector of the pulsation, n_f is the faults numbers (in this study $n_f = 1$).

$$\delta(\omega_s) = \begin{pmatrix} 0 & \omega_s \\ -\omega_s & 0 \end{pmatrix}$$

Where ω_s the pulsation of the harmonic generated by the stator 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 perturbing terms in (22) can be as a suitable combination of the exosystem state, namely:

$$\begin{pmatrix} i_d \rightarrow i_d + Q_d w \\ i_q \rightarrow i_q + Q_q w \end{pmatrix} \quad (18)$$

With: $\begin{pmatrix} Q_d = (1 & 0 & 1 & 0 & \dots & 1 & 0) \\ Q_q = (0 & 1 & 0 & 1 & \dots & 0 & 1) \end{pmatrix}$

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 (18) the ($i_d - i_q$) modify as:

$$\begin{pmatrix} \frac{di_d}{dt} = \dot{x}_1 = a_1 x_1 + a_2 x_2 x_3 + b_1 u_d \\ \quad -(a_1 Q_d + a_2 Q_q x_3 + Q_d \delta(\omega_s))w \\ \frac{di_q}{dt} = \dot{x}_2 = a_3 x_2 + a_4 x_3 + a_5 x_1 x_3 + b_2 u_q \\ \quad -(a_3 Q_d + a_4 Q_q x_3 + Q_d \delta(\omega_s))w \end{pmatrix} \quad (19)$$

Taking account the stator currents dynamics in the normal (i.e., in the absence of faults) operative conditions, it is also simple to get the PMSM dynamics in faulty condition:

$$\begin{cases} \dot{x}_1 = a_1 x_1 + a_2 x_2 x_3 + b_1 u_d + \Gamma_d w \\ \dot{x}_2 = a_3 x_2 + a_4 x_3 + a_5 x_1 x_3 + b_2 u_q + \Gamma_q w \\ \dot{x}_3 = a_6 x_2 + a_7 x_3 + dT_L \end{cases} \quad (20)$$

With: $\begin{cases} \Gamma_d = -(a_1 Q_d + a_2 Q_q x_3 + Q_d \delta(\omega_s)) \\ \Gamma_q = -(a_3 Q_d + a_5 Q_q x_3 + Q_d \delta(\omega_s)) \end{cases}$

2. Control reconfiguration

The idea behind FTC is that of designing a control unit able to automatically offset the faults effect, without need of an explicit FDI process and consequent explicit reconfiguration. This objective will be pursued for the PMSM by means of the control law sketched in (21). In this later, an additive control law (u_{ad}) resulting from the internal model is added to the proposed SMC with integral surface (u_{nom}) and setting to compensate the faults effect.

$$u = u_{nom} + u_{ad} \quad (21)$$

With: $u = \begin{pmatrix} u_d \\ u_q \end{pmatrix}; u_{nom} = \begin{pmatrix} u_d^{nom} \\ u_q^{nom} \end{pmatrix}; u_{ad} = \begin{pmatrix} u_d^{ad} \\ u_q^{ad} \end{pmatrix}$

Starting from the resent works presented in [13-14] and in order to determine the unknown term u_{ad}; let as present the instantaneous difference between the system state derivative (10) and the references:

$$\begin{pmatrix} \dot{e}_d \\ \dot{e}_q \\ \dot{e}_\omega \end{pmatrix} = \begin{pmatrix} \dot{x}_1 - \dot{x}_1^* \\ \dot{x}_2 - \dot{x}_2^* \\ \dot{x}_3 - \dot{x}_3^* \end{pmatrix} = \begin{pmatrix} f_1(x) + b_1 u_d - \dot{x}_1^* - \Gamma_d w \\ f_2(x) + b_2 u_q - \dot{x}_2^* - \Gamma_q w \\ f_3(x) - \dot{x}_3^* \end{pmatrix} \quad (22)$$

From the nominal control law described in (10) and from the global control law (21) after replacing in (22) we get:

$$\begin{pmatrix} \dot{e}_d \\ \dot{e}_q \\ \dot{e}_\omega \end{pmatrix} = \begin{pmatrix} -m_3 e_d + b_1 u_d^{ad} - \Gamma_d w \\ -m_2 e_q + b_2 u_q^{ad} - \Gamma_q w \\ -m_1 e_\omega \end{pmatrix} \quad (23)$$

Let us notice that the first two equations depend' not on e_ω. In the continuation, for the determination of u_{ad} let us consider the subsystem:

$$\tilde{x} = \begin{pmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{pmatrix} = \begin{pmatrix} e_d \\ e_q \end{pmatrix} \quad (24)$$

Whose dynamics results from the system (23) as follow:

$$\begin{pmatrix} \dot{\tilde{x}}_1 \\ \dot{\tilde{x}}_1 \end{pmatrix} = \begin{pmatrix} -m_3 e_d + b_1 u_d^{ad} - \Gamma_d w \\ -m_2 e_q + b_2 u_q^{ad} - \Gamma_q w \end{pmatrix} \quad (25)$$

Then, system (25) can be written in matrix form:

$$\dot{\tilde{x}} = H(\tilde{x}) + \tilde{B} \cdot u_{ad} - \Gamma \cdot w \quad (26)$$

With: $\begin{cases} H(\tilde{x}) = \tilde{A} \cdot \tilde{x} \;\; and \;\; \tilde{A} = \begin{pmatrix} -m_3 & 0 \\ 0 & -m_2 \end{pmatrix} \\ \tilde{B} = \begin{pmatrix} b_1 & 0 \\ 0 & b_2 \end{pmatrix} \;\; and \;\; \Gamma = \begin{pmatrix} \Gamma_d & 0 \\ 0 & \Gamma_q \end{pmatrix} \end{cases}$

Indeed, several applications based internal model has been discussed at several papers recently [13], [14] and [17]. In this paper in order to design a FTC approach we need to introduce the internal model this later based Lyapunov theory which takes the following form:

$$\begin{cases} \dot{\xi} = \delta(\omega_s)\xi + N(\tilde{x}) \\ \dim(\xi) = \dim(w) = 2n_f \end{cases} \quad (27)$$

Then u_{ad} is designed as ([12] and [16]):

$$u_{ad} = \tilde{B}^{-1} \Gamma \xi \quad (28)$$

3. Closed loop stability analysis:

Consider the systems (26) and the additive term given by (28) in this case we have:

$$\dot{\tilde{x}} = H(\tilde{x}) + \Gamma \cdot (\xi - w) \quad (29)$$

The new error variable is considered:

$$e = (\xi - w) \quad (30)$$

Its derivative compared to time takes this form:

$$\dot{e} = \dot{\xi} - \dot{w} = \delta(\omega_s)\xi + N(\tilde{x}) + \delta(\omega_s)w \qquad (31)$$

The equations describing the dynamics of the errors in closed loop can be written as:

$$\begin{cases} \dot{\tilde{x}} = \tilde{A}\cdot\tilde{x} + \Gamma\cdot e \\ \dot{e} = \delta(\omega_s)e + N(\tilde{x}) \end{cases} \qquad (32)$$

To find the expression of $N(\tilde{x})$ which cancels the faults error e and at the same time makes it possible to reject their effect, let's define the Lyapunov function of the system (32):

$$V = \frac{1}{2}\tilde{x}^T\cdot\tilde{x} + \frac{1}{2}e^T\cdot e \qquad (33)$$

After calculate development $\dot{V}$ becomes:

$$\dot{V} = \tilde{x}^T\cdot\tilde{A}\cdot\tilde{x} + e^T\cdot\Gamma^T\cdot\tilde{x} + e^T\cdot N(\tilde{x}) \qquad (34)$$

Then, we must take the expression of $N(\tilde{x})$ as:

$$N(\tilde{x}) = -\Gamma^T\tilde{x} \qquad (35)$$

At the end from (34) and (35) the derivative of Lyapunov function becomes:

$$\dot{V} = \tilde{x}^T\cdot\tilde{A}\cdot\tilde{x} \le 0 \qquad (36)$$

Finally, the objective of the control is achieved by adopting the procedure suggested. Then, it's 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 this paper, to validate the proposed scheme the simulation model is established under the circumstance of MATLAB-Simulink according to the established mathematic model, and the simulation results are shown in Figures 2-3. Indeed, the parameters of PMSM used in this simulation are as follows:

The effectiveness of the motor speed and currents controllers are proved by two groups' simulation under healthy and faulty conditions. Figures 2 and 3 show the responses of the motor speed, currents, and torque when stator fault appear at $t = 0.4$ s under the condition that $T_L = (0.05\text{ Nm})$, $\omega_r^* = 100\,(\text{red/s})$ and $i_d^* = 0\,(\text{A})$.

Rated Values	Power	22	W
	Frequency	50	Hz
	n_p	2	
Rated parameters	R_s	3.4	Ω
	L_d	0.0121	H
	L_q	0.0121	H
	φ_f	0.4212	H
	J	0.0001	Kg.m^2
	f	0.0005	IS

As can be seen from Figures 2 and 3, the proposed SMC augmented by integral switching surface (nominal controller) present a robustness compared to the load torque disturbance, but proves to be insufficient in the event of stator fault. This is checked by simulations represented above when the *internal model* is not active (see Fig.2).

Fig.3 shows the responses of the global closed loop system with the FTC based SMC. From this figure we can notice that the proposed FTC approach (*when the internal model is active*) rejects the load torque disturbances also the eccentricity fault.

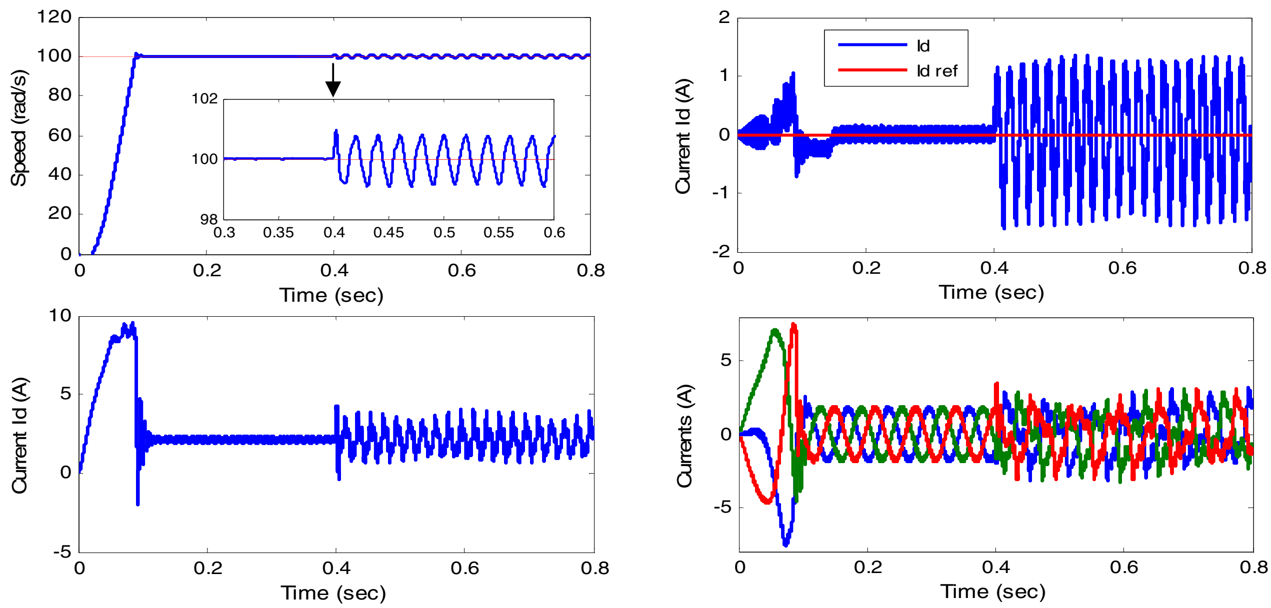

Fig.2. Simulation of PMSM under stator fault controlled by SMC strategy (without FTC approach).

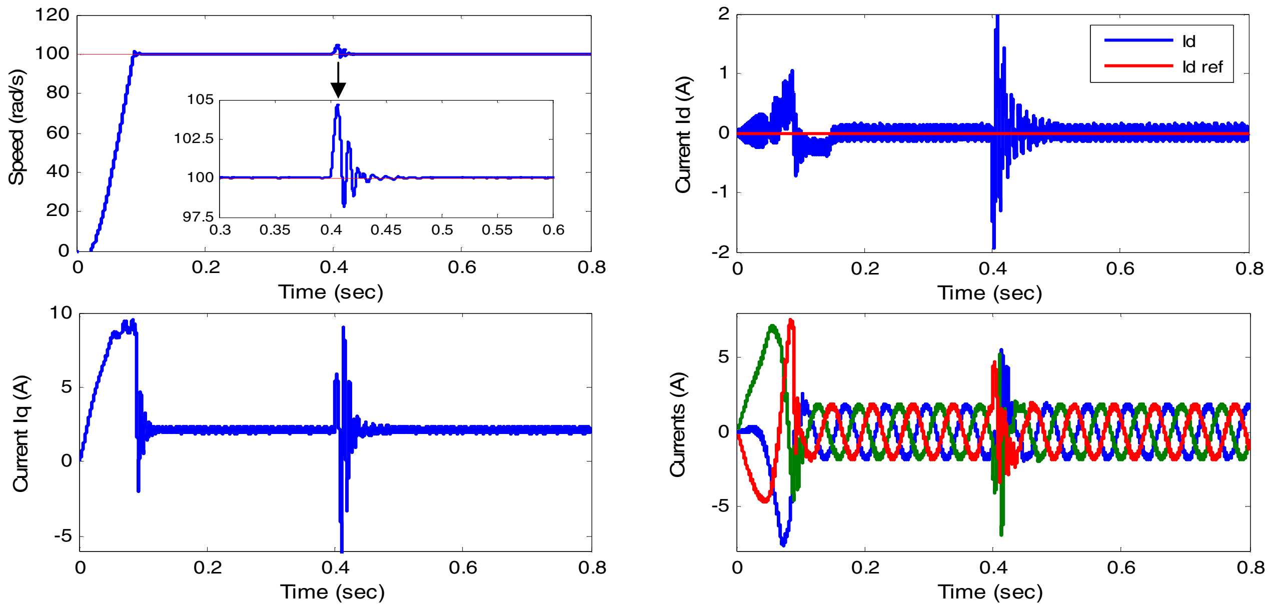

Fig.3. Simulation of PMSM under stator fault controlled by SMC strategy (with the proposed FTC approach)

VI. Conclusion

A novel fault tolerant concept using SMC augmented by integral switching surface has been proposed in this paper to improve control performance of permanent magnet synchronous motors. In un-faulty condition the SM controller permits to steer the direct current and the speed variables to their desired references and to reject the parametric and load torque disturbances, however the presence of static eccentricity faults degraded the PMSM performances. In order to deal with this fault a FTC approach can be designed starting with generating from a simple internal model, an additive term which we add to the nominal control (SMC). Obviously, simulation results indicate that the proposed control scheme eliminates the fault effect, and holds the advantages of fast response and strong robustness.

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