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Fault Tolerant Control of DTC Controlled Induction Motors subject to Interturn Faults

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***Abstract*—The paper describes a Fault Tolerant Control (FTC) of Induction Motors (IM) based Direct Torque Control (DTC). We study the case of stator inter-turn fault, which is the most frequently encountered in practice. An analytical method for the modeling of this fault has been presented including space harmonics effect. The obtained model is less complicated to be implemented for condition monitoring or to validate FTC algorithms. The equations which describe the transients as well as steady states behavior including the computation of machine inductances are presented. Simulation results show, on the one hand that the proposed control scheme provides high-performance dynamic characteristics, and on the other hand the applicability and the tolerance of this control.**

Keywords- Adaptive observer, direct torque control, interturn faults, magnetic coupled circuit.

I. INTRODUCTION

Induction machine is used in wide variety of applications. Industrial drives, pumps and electric traction are but few applications of large IM. However, the IM are subject to many faults, due to a combination of thermal overloading, transient voltage stresses, mechanical stresses and environmental stresses [1-4]. From a number of surveys, it can be deduced that inter-turn fault accounts approximately 40% of all failures [5-8]. The research on condition monitoring and fault tolerant control of IM often needs an accurate model. For this purpose, we have to elaborate a model which enables us to predict the performances and to extract fault signatures on electromagnetic torque, stator current and magnetic field. In a real machine, the magnetomotive force (MMF) produced is not sinusoidally distributed in the air-gap. The harmonics in the MMF have a significant detrimental effect on the performances of the machine [9-10]. Particularly, they influence the harmonic content of the stator currents which can be used for monitor internal faults or for fault tolerant control of IM. The harmonic inductances can be calculated using the magnetic field distribution, which can be evaluated analytically from the machine structure. The obtained model gives a good compromise between modeling accuracy and simulation time.

For controlled IM drives, the FTC preserves the pre-specified performances: continuity, quality of services and stability despite the presence of faults. Some FTC schemes require explicit detection and estimation of the fault (active FTC), while some FTC schemes operate using robust controller without such explicit detection (passive FTC) [11-14].

For conventional DTC, the stator flux is obtained from the stator voltage model, using the measured stator voltages and currents [15-16]. This method, utilizes open loop pure integration, suffers from the well known problems, especially at low speeds operation mode [17].

For closed loop estimation, the state estimation is affected by parameter variation, especially the stator resistance, particularly at low speeds [18-19]. Therefore, to improve the estimation of the stator flux components, it's necessary to compensate this parameter variation by using an online adaptation [20]. So, the proposed FTC is a combination between an active and passive FTC. The advantage of this FTC is that when the fault is not tolerant an alarm signal will indicate that the operator's intervention is necessary.

II. CALCULATION OF MACHINE INDUCTAQNCES

A. *Windings distributrion*

In order to obtain the machine inductances, firstly should be obtained the spatial distribution of magnetomotive force produced by a phase "j" of the stator windings. Using this distribution it is possible to get the harmonic components of magnetic flux linkage between the two phases "i" and "j". These harmonics of flux linkage create the harmonic inductances. Self inductances are obtained for i = j and mutual inductance for i ≠ j. To illustrate the calculation of the machine inductances, it is convenient to consider the elementary 2-poles, star connected three phase induction machine. The stator windings are concentric with consequent poles. This distribution configuration corresponds more to the real situation induction machines [15]. Each phase is composed of four coils in series as shown in Fig. 1.

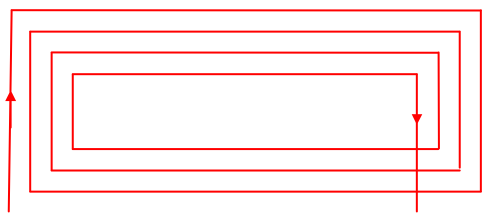

Figure 1. Concentric windings with consequent poles.

B. Spacial Distribution of Magnetomotive Force

The MMF of the stator winding “j” through the machine air-gap is represented as follows.

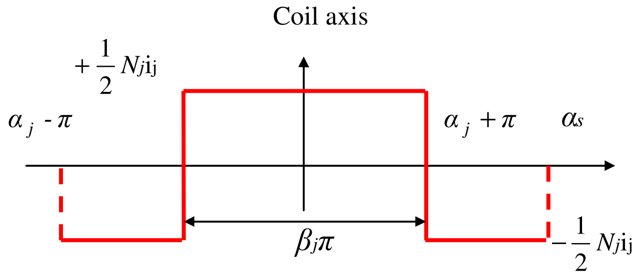

Figure 2. MMF distribution of a generic coil.

The MMF distribution is expressed represented by the following equation when submitted to a current i_j.

$$w_{cs}(\alpha_s) = \begin{cases} -\frac{1}{2}N_j i_j & \Rightarrow \quad \alpha_j - \pi \le \alpha_s \le \alpha_j - B_j\frac{\pi}{2} \\ +\frac{1}{2}N_j i_j & \Rightarrow \quad \alpha_j - B_j\frac{\pi}{2} \le \alpha_s \le \alpha_j + B_j\frac{\pi}{2}. \\ -\frac{1}{2}N_j i_j & \Rightarrow \quad \alpha_j + B_j\frac{\pi}{2} \le \alpha_s \le \alpha_j + \pi \end{cases} \tag{1}$$

A decomposition of $W_{cs}(\alpha_s)$ in its Fourier series gives

$$w_{cs}(\alpha_s) = \frac{2}{\pi}N_j i_j \sum_{h=1}^{\infty}\frac{1}{h}\sin\left(h\beta_j\frac{\pi}{2}\right)\cos\left(h(\alpha_s - \alpha_j)\right) \tag{2}$$

h : Harmonic order

α_s : Angular position which locates any point along the circumference of the air-gap from a fixed reference.

α_j : Value of α_s in through the centre of coil.

Each of the q_j coils is the origin of an order h harmonic component of MMF which can be extracted from (2)

$$w_{ch}(\alpha_s) = \frac{2}{\pi}N_j i_j \frac{1}{h}\sin(h\beta_j\frac{\pi}{2})\cos\left(h(\alpha_s - \alpha_j)\right). \tag{3}$$

For any winding of phase j, the harmonic component “h” of the spatial distribution of MMF in the air-gap can be obtained by superposition of space harmonics with the same order from the phase coils. The MMF distribution for phase j to the harmonic order h is

$$w_{jh}(\alpha_s) = \frac{1}{h}\frac{2}{\pi}i_j\sum_{j=1}^{q_j} N_j \sin(h\,\beta_j\frac{\pi}{2})\cos\left(h(\alpha_s - \alpha_j)\right) \tag{4}$$

where q_j is the number of distribution coils in phase j.

C. Harmonic Inductances of Stator Windings

Magnetic field distribution $B_{jh}(\alpha_s)$ produced by $w_{jh}(\alpha_s)$ is obtained through the application of Ampére law in the air-gap only; the magnetic circuit reluctance in the iron parts is neglected. Consequently, the magnetic field distribution is

$$B_{jh}(\alpha_s) = \frac{\mu_0}{g} w_{jh}(\alpha_s) \tag{5}$$

Where μ_0 the air magnetic permeability and g is the air-gap length. Space distribution $B_{jh}(\alpha_s)$ gives origin to a component of harmonic order “h” of the mutual flux in an order “b” coil for the phase “i” winding given by

$$\lambda_{jh} = P\int_{\alpha_i+\beta_i\pi}^{\alpha_i+\beta_i\pi} B_{jh}(\alpha_s) rL\, d\alpha_s \tag{6}$$

L : Magnetic length of the rotor.

r : Average radius of the air-gap.

Taking in consideration phase “i” made by distribution q_i of coils, the flux linkage between phases “j” and “i” is expressed

$$\lambda_{jih} = \frac{1}{h^2}\frac{4}{\pi}\frac{\mu_0 rL}{g}\cos\left(h(\alpha_j - \alpha_i)\right)i_j\sum_{j=1}^{q_i} N_j \sin(h\,\beta_j\frac{\pi}{2})\sum_{i=1}^{q_i} N_i \sin(h\,\beta_i\frac{\pi}{2}) \tag{7}$$

Thus, the harmonic inductance between phases “i” and “j” is

$$L_{jih} = \frac{2}{\pi}\frac{\mu_0 rL}{g}\frac{1}{h^2}\cosh(\alpha_j - \alpha_i)\sum_{j=1}^{q_i} N_j \sin(h\beta_j\frac{\pi}{2})\sum_{i=1}^{q_i} N_i \sin(h\beta_i\frac{\pi}{2}) \tag{8}$$

Consequently, the mutual inductance is in the form

$$L_{ij} = \frac{2}{\pi}\frac{\mu_0 rL}{g}\sum_{h=1}^{\infty}\frac{1}{h^2}\cosh(\alpha_j - \alpha_i)\sum_{j=1}^{q_i} N_j \sin(h\beta_j\frac{\pi}{2})\sum_{i=1}^{q_i} N_i \sin(h\beta_i\frac{\pi}{2}) \tag{9}$$

For i = j, we obtain the magnetizing inductance

$$L_{ms} = \frac{2}{\pi}\frac{\mu_0 rL}{g}\sum_{h=1}^{\infty}\frac{1}{h^2}\sum_{i=1}^{q_i} N_i \sin(h\beta_j\frac{\pi}{2})\sum_{i=1}^{q_i} N_i \sin(h\beta_i\frac{\pi}{2}). \tag{10}$$

D. Mutual Inductance Stator-Rotor

To obtain the harmonic mutual inductance between the stator phase “j” and any rotor loop, firstly should be obtained the component of harmonic order “h” of the mutual flux in the rotor loop. This component is expressed

$$\lambda_{jrh} = \int_{\theta_k}^{\theta_k+\alpha_r} B_{jh}(\alpha_s) rL\, d\alpha_s \tag{11}$$

θ_k : Angular position of the rotor loop of order “k”.

α_r : Rotor loop pitch.

The flux linkage between phase "j" and the rotor loop of order "k" is

$$L_{jr} = \frac{4}{\pi}\frac{\mu_0 rL}{g}\sum_{h=1}^{\infty}\frac{1}{h^2}\cosh(\theta_k - \alpha_j - \delta)\sum_{j=1}^{q_j} N_j \sin(h\beta_j \frac{\pi}{2}) \quad (12)$$

$$\delta = \frac{\alpha_r}{2} \quad (13)$$

$$\theta_k = \theta_r + (k-1)\alpha_r. \quad (14)$$

θ_r : Angular position of the first rotor loop.

III. MODFELLING OF INTERTURN FAULTS

A. *General Considerations*

In induction machines, coils are insulated one from other in slots as in end winding region. The biggest probability for inter-turn fault is inter-turn between turns in the same coil. When an inter-turn fault occurs, the phase winding has less turns. As a result of the inter-turn fault, the mutual between the phase in which inter-turn is occurred and all of the circuits in machine are altered. Initially, we consider the sample example, where the coil U-V has four turns and occupied two slots. When, a short circuit occurred between the contact points c_1 and c2, three turns in series are obtained. In addition, a new short-circuited turn which we call the short circuited phase D is created and magnetically coupled with all the other circuits. It is evident that the phase current and the currents which follow in the short-circuited phase produce opposite MMFs. Therefore, inter-turn short circuits have a cumulative effect in decreasing the total MMF produced in the air-gap.

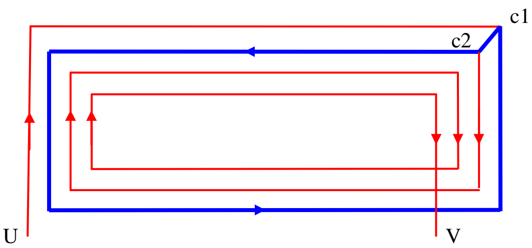

Figure 3. Short-circuited coil

B. *Spacial Distribution of Magnetomotive Force*

The new phase D is described by the voltage equation

$$r_d i_d + \frac{d\Phi_d}{dt} = 0 \quad (15)$$

Where Φ_d , i_d and r_d are respectively the magnetizing flux, the current and the resistance of the new phase D.

Applying the previous method for the calculation of machine inductances, we obtain the self and mutual inductance of the new phase and all the other circuits.

C. *Stator Voltage Equations*

In the case of unbalanced conditions, we employ line to line voltages as inputs in simulation model [16]. The stator voltage equation becomes

$$u_s = R_s i_s + \frac{d\varphi_s}{dt} \quad (16)$$

$u_s = [u_{ab}\ u_{bc}\ u_{ca}\ 0]^T$

$i_s = [i_{as}\ i_{bs}\ i_{cs}\ i_d]^T$

$$R_s = \begin{bmatrix} r_{as} & -r_{bs} & 0 & 0 \\ 0 & +r_{bs} & -r_{cs} & 0 \\ -r_{as} & 0 & +r_{cs} & 0 \\ 0 & 0 & 0 & +r_d \end{bmatrix} \quad (17)$$

u_{ab}, u_{bc} and u_{ca} are the line to line voltages.
i_{as}, i_{bs} and i_{cs} are the line currents.
r_{as}, r_{bs} and r_{cs} are the resistances of stator windings.

The flux equations are expressed

$$\varphi_s = A\Phi_s \quad (18)$$

$$\Phi_s = L_{ss} i_s + L_{sr} i_r \quad (19)$$

$$A = \begin{bmatrix} +1 & -1 & 0 & 0 \\ 0 & +1 & -1 & 0 \\ -1 & 0 & +1 & 0 \\ 0 & 0 & 0 & +1 \end{bmatrix} \quad (20)$$

L_{ss} , and L_{sr} are the matrices of the stator, and the stator-rotor mutual inductances. i_r is the rotor vector current.

When a number short-circuited turns are created. The new short-circuited turns are identical and have no conductive contact with other phases. They can be analyzed with the same manner as the case of one short-circuited turn. The defect phase short-circuit factor is defined by

$$kcc\% = 100\frac{N_{cc}}{N_s} \quad (21)$$

N_s is the number of turns in healthy condition.
N_{cc} is the number of short-circuited turns.

D. Rotor Voltage Equations

The voltage equation for the rotor circuit is expressed

$$0 = R_r i_r + \frac{d\Phi_r}{dt} \tag{22}$$

The rotor flux is expressed

$$\Phi_r = L_{rs} i_s + L_{rr} i_r \tag{23}$$

$$\boldsymbol{L}_{rs} = (\boldsymbol{L}_{sr})^T \tag{24}$$

Where $\boldsymbol{L}_{rr}$ and $\boldsymbol{L}_{rs}$ are the matrices of the rotor, the rotor-stator mutual inductances respectively.
The mechanical equation is expressed

$$J\frac{d}{dt}\Omega = T_e - T_l - f_v\Omega \tag{25}$$

Where J *is* the inertia of the rotor and the connected load, T_e the electromagnetic torque, T_l the load torque, Ω the mechanical angular speed and f_v is the viscose friction coefficient. The electromagnetic torque can be expressed [6]

$$T_e = \frac{P}{2}(\boldsymbol{i}_s)^T \frac{\partial L_{sr}}{\partial \theta_r}(\boldsymbol{i}_r) \tag{26}$$

Where P is the number of poles and θ_r is the electrical angular displacement of the rotor.

IV. FTC DESIGN

The global FTC scheme is represented as follows.

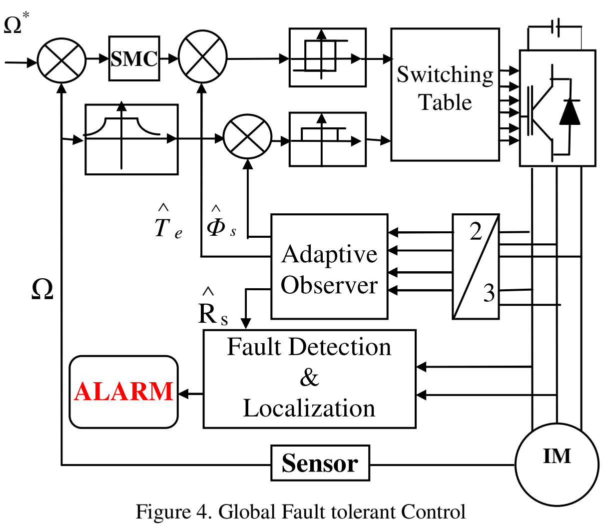

Figure 4. Global Fault tolerant Control

A. Fault Detection and Localization Unit

The fault detection and localization unit detects the occurence of fault and determines its nature. This can be realized by analyzing the harmonic content of stator currents or by analyzing the change of the stator resistance and then take the appropriate decision: accept the default or stop the machine and execute a curative maintenance.

B. Adaptive Observer

The objective is to determine the mechanism adaptation of the speed and the stator resistance. The structure of the observer is based on the induction motor model in stator reference frame. The adaptive observer is of the following structure.

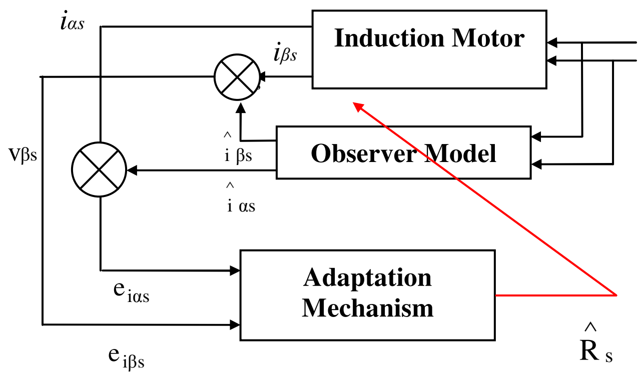

Figure 5. Global adaptive observer

The state equations of the induction motor can be expressed as follows [21]

$$\begin{cases} \dfrac{di_{\alpha s}}{dt} = -\dfrac{1}{\sigma L_s}\left(R_s + R_r\dfrac{L_m^2}{L_r^2}\right)i_{\alpha s} + \dfrac{1}{\sigma L_s}R_r\dfrac{L_m}{L_r^2}\Phi_{\alpha r} + \dfrac{1}{\sigma L_s}\omega\dfrac{L_m}{L_r}\Phi_{\beta r} + \dfrac{1}{\sigma L_s}v_{\alpha s} \\ \dfrac{di_{\beta s}}{dt} = -\dfrac{1}{\sigma L_s}\left(R_s + R_r\dfrac{L_m^2}{L_r^2}\right)i_{\beta s} - \dfrac{1}{\sigma L_s}\omega\dfrac{L_m}{L_r}\Phi_{\alpha r} + \dfrac{1}{\sigma L_s}R_r\dfrac{L_m}{L_r^2}\Phi_{\beta r} + \dfrac{1}{\sigma L_s}v_{\beta s} \\ \dfrac{d\Phi_{\alpha r}}{dt} = \dfrac{R_r L_m}{L_r}i_{\alpha s} - \dfrac{R_r}{L_r}\Phi_{\alpha r} - \omega\Phi_{\beta r} \\ \dfrac{d\Phi_{\beta r}}{dt} = \dfrac{R_r L_m}{L_r}i_{\beta s} - \dfrac{R_r}{L_r}\Phi_{\beta r} + \omega\Phi_{\alpha r} \end{cases} \tag{27}$$

Where $v_{\alpha s}$, $v_{\beta s}$ are the components of stator voltage vector, i_{ds}, i_{qs} are the components of stator current vector, $\Phi_{\alpha r}$, $\Phi_{\beta r}$ are the components of rotor flux vector, σ is the leakage factor, R_s and R_r are stator and rotor resistance, L_s and L_r represent the stator and rotor cyclic inductances and L_m is the stator-rotor cyclic mutual inductance. ω_s, ω are the stator and mechanical pulsation.

The previous state system can be expressed in the form

$$\begin{cases} \dfrac{dX}{dt} = AX + BU \\ Y = CX \end{cases} \tag{28}$$

With:

$$X^T = \left(i_{\alpha s}\ i_{\beta s}\ \Phi_{\alpha r}\ \Phi_{\beta r}\right), Y = \begin{pmatrix} i_{\alpha s} \\ i_{\beta s} \end{pmatrix},\ U = \begin{pmatrix} v_{\alpha s} \\ v_{\beta s} \end{pmatrix}$$

The matrices are defined by

$$A = \begin{pmatrix} -a & 0 & \dfrac{R_r L_m}{L_r b} & \omega \dfrac{L_m}{b} \\ 0 & -a & -\omega \dfrac{L_m}{b} & \dfrac{R_r L_m}{L_r b} \\ \dfrac{R_r L_m}{L_r} & 0 & -\dfrac{R_r}{L_r} & -\omega \\ 0 & \dfrac{R_r L_m}{L_r} & +\omega & -\dfrac{R_r}{L_r} \end{pmatrix}$$

$$B = \begin{pmatrix} \dfrac{1}{\sigma L_s} & 0 \\ 0 & \dfrac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{pmatrix},\ C = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

$$a = \frac{1}{\sigma L_s}\left(R_s + R_r \frac{L_m^2}{L_r^2}\right),\ b = \sigma L_s L_r,\ \sigma = 1 - \frac{L_m^2}{L_s L_r}$$

A linear state observer can then be derived as follows by considering the mechanical speed as a constant parameter during a sampling time since its variation is very slow.

The model of the observer is written [24]

$$\begin{cases} \dfrac{d\hat{X}}{dt} = \hat{A}\hat{X} + BU + G\left(Y - \hat{Y}\right) \\ \hat{Y} = C\hat{X} \end{cases} \tag{29}$$

The machine parameters are assumed to be perfectly known, the stator resistance is unknown. We define

$$\delta R_s = R_s - \hat{R}_s \tag{30}$$

The symbol $\wedge$ denotes estimated values and G is the observer gain matrix. We will determine the differential system describing the evolution of the error

$$e = X - \hat{X} \tag{31}$$

The state matrix of the observer can be written as

$$\hat{A} = A + \delta A \tag{32}$$

With

$$\delta A = \begin{pmatrix} -\dfrac{1}{\sigma L_s}\delta R_s & 0 & 0 & 0 \\ 0 & -\dfrac{1}{\sigma L_s}\delta R_s & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{33}$$

Then, we can write

$$\frac{d\hat{X}}{dt} = \hat{A}\hat{X} + BU + G\left(Y - \hat{Y}\right) \tag{34}$$

We define the Lyapunov function

$$V = e^T e + \frac{(\delta R_s)^2}{\lambda} \tag{35}$$

λ is positive scalar. This function should contain terms of the difference δR_s to obtain mechanism adaptation. The stability of the observer is guaranteed for the condition [25]

$$\frac{dV}{dt} < 0 \tag{36}$$

We consider the hypothesis of a slowly varying regime for the machine parameters, thus

$$\frac{dR_s}{dt} \approx 0 \tag{37}$$

We obtain the adaptation mechanism in the form [20]

$$\hat{R}_s = \int -\lambda \frac{1}{\sigma L_s}\left(\hat{i}_{\alpha s}\, e_{i\alpha s} + \hat{i}_{\beta s}\, e_{i\beta s}\right) dt \tag{38}$$

The matrix of gain G is selected such as the eigenvalues of the matrix $A - GC$ are in the left plane half of the complex plan and that the real part of the eigenvalues is larger in absolute value than the real part of the eigenvalues of the state matrix A [24].

The estimated electromagnetic torque is expressed

$$\hat{C}_e = \frac{3}{2} p \frac{L_m}{L_r} \left(\hat{\Phi}_{\alpha r} \hat{i}_{\beta s} - \hat{\Phi}_{\beta r} \hat{i}_{\alpha s} \right) \tag{39}$$

V. SIMULATION RESULTS

The technique presented in the previous sections, has been implemented in the MATLAB environment. To illustrate performances of the proposed control, particularly at low speeds, we simulated the healthy and faulty modes. The synthesized observer allows us to reconstruct all the state variables. For the DTC simulation, torque and flux hysteresis bands are 0.2 Nm and 0.01 Wb respectively.

A. *Healthy Operation*

We simulated a loadless starting up mode with reference speed of -50 rpm; at t = 0.25 sec, the reference speed is inversed and becomes +50 rpm, then at t = 0.8 sec, sudden changes in load torque of 13.5 Nm is occurred and at t = 1 sec, the stator resistance increases of 50 % as a result of elevation of temperature. The simulation results are as follows.

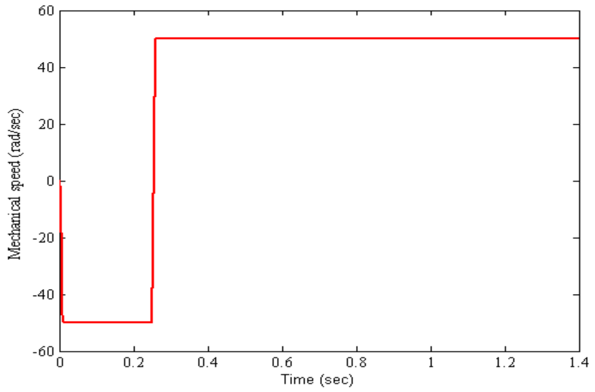

Figure 6 Rotor speed

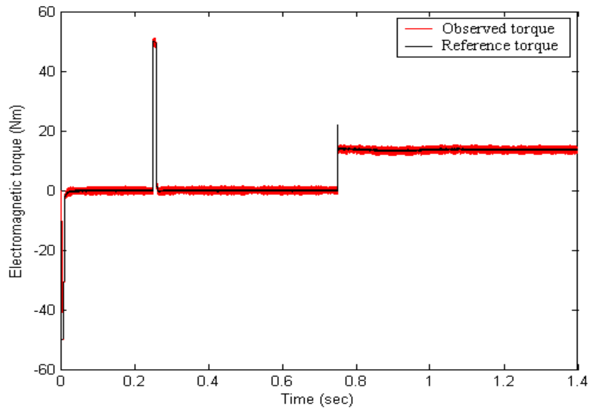

Figure 7. Electromagnetic torque

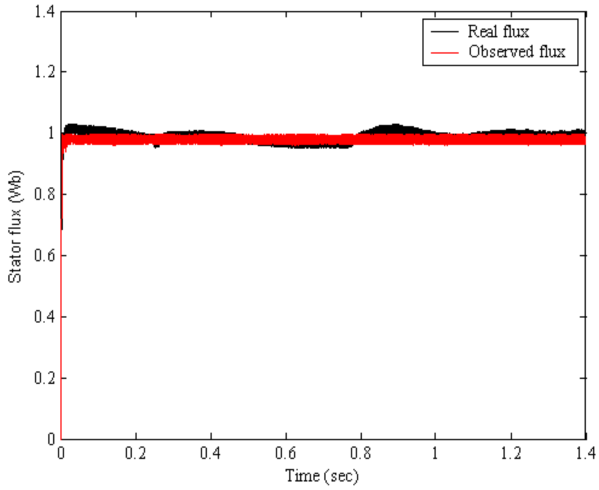

Figure 8. Magnitude of stator flux

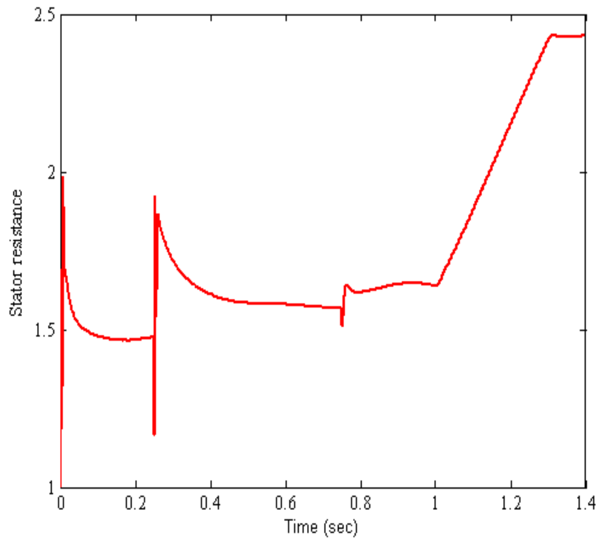

Figure 9. Observed stator resistance

It is clear that the external disturbances like changes in load torque, reference speed or stator resistance variation don't allocate the performances of the proposed control. The flux tracks the reference value and it is insensitive to parameters variation. The speed response also stays insensitive to parameters variation. The global control scheme introduces high performances of robustness, stability and precision, particularly, under uncertainties caused by parameter variation.

B. *Faulty Operation*

We simulated a load starting up mode with a speed of reference equals to +50 rpm with an interturn fault of 5 % on the first winding. The simulation results are as follows.

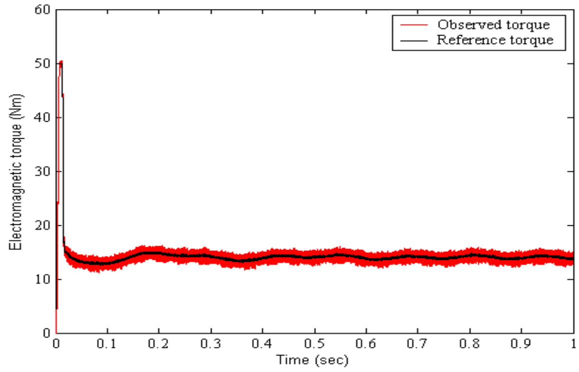

Figure 10. Electromagnetic torque

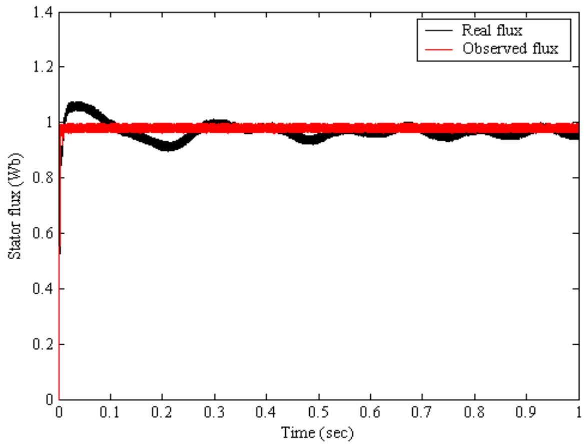

Figure 11. Magnitude of stator flux

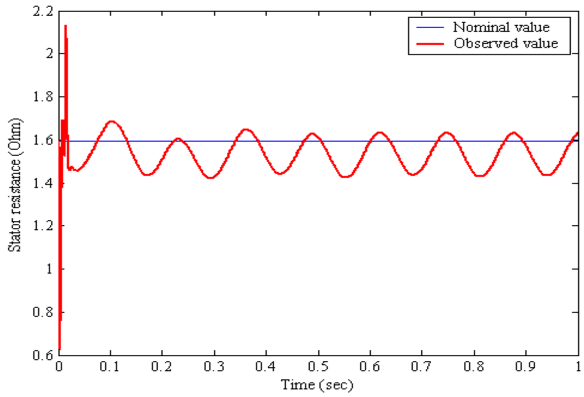

Figure 12. Observed stator resistance

In faulty conditions, the machine is unbalanced. The stator resistance oscillates below its nominal value. At low speeds, the faulty harmonics are near the fundamental and the distinction between the different harmonics becomes very difficult. The observed stator resistance will be a very interesting tool for fault detection. In this condition, the stator resistance is a fictitious quantity which only serves to superpose the Clarck model to the faulty one. In addition, the adaptation of this resistance serves to improve the robustness of the observer.

CONCLUISION

A new approach to induction machine modeling has been presented including space harmonics effect. It can be readily applied for the analysis of stator and rotor faults of IM drives. In faulty conditions, the machine is unbalanced and significant increase of stator currents is produced. For the proposed control scheme, the speed remains equal to its reference value and the overshoot currents can not be avoided. When the current is not exceeding the acceptable level, the machine continues to operate with degraded performances until its repair or exchange. So, it's always necessary to execute early fault detection for less damage. The global control scheme introduces high performances of robustness; stability and precision. The proposed approach relies on the improvement of an estimation of the stator flux components. The estimation of the stator flux by the adaptive observer has well made more robust stable the FTC of IM based DTC.

SIMULATED MACHINE PARAMETERS

Stator phase resistance	$r_s = 1.5950\ \Omega$
Rotor phase resistance	$r_r = 1.3053\ \Omega$
Effective air-gap	$g = 0.35$ mm
Stack length	$L = 125$ mm
Rotor radius	$r = 37.35$ mm
Stator phase leakage inductance	$L_{ls} = 0.0040$ H
Rotor phase leakage inductance	$L_{lr} = 0.0033$ H
Drive inertia	$J = 0.045\ \text{kg.m}^2$
Friction coefficient	$f_v = 0.0038\ \text{kg.m}^2.\text{s}^{-1}$
Stator phase turns	$N_s = 124$
Rotor bar resistance	$r_b = 3.04E{-}4\ \Omega$
Rotor end ring segment resistance	$r_e = 8.75E-7\ \Omega$
Rotor bar leakage inductance	$l_b = 5.16E-7$ H
End ring segment leakage inductance	$l_e = 1.59E-9$ H

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