Sliding Mode Control for Speed of an Induction Motor with Broken Rotor Bars

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***Abstract* — The traditional control of induction motor is not enough, because it lacks robustness, especially when the demand for accuracy and other dynamic characteristics of the system are of better performances in nowadays industry. But induction may face some disturbances, such as: electrical and mechanical faults as : broken bars**

Many researchers have proposed several techniques for achieving good performance of the induction motors, Sliding mode control is one of the methodologies, that recently have become the main operational mode. The paper will analyse the control of sliding mode applied upon inductions motors under the effect of broken bars rotor, and load torque variation, the simulation is implemented using MATLAB/ SIMULINK, the performance of the system is illustrated through simulation.

Keywords—induction motor, sliding mode control, broken bar, Robustness.

I. INTRODUCTION

The so many demands for developed induction motors, which are able of ensuring both good robustness and simple maintenance are increasingly gowing in the modern time.

These demonds, are growing because they can guarantee good or better performance in the industrials. And techno sectors. Though induction motors are vital and benefitial, they face some difficulties as these: mechanical and electrical faults, broken bars, short circuits,……etc[1][2]

The developments of power electronics and theories of control else the electrical techniques pushed people to use the induction motors, that are of high performance, especially when talking about the industrial side[3]. A lot of researchers, focused on finding techniques that are capable of achieving good performance of induction motors, taking into consideration the existence of some faults.

Sliding mode control is considered as one of the methodologies that recently have become the main operational mode[4]. This interest is related to facts as: the robustness, the non-linearity and its ability of reaching the upper limits during the minimum time.[5][6]

II. MODEL WITH FAULT OF INDUCTION MOTOR FOR ITS CONTROL

For developing approaches that are able of guaranteeing the wished performance, the need for a model to which can reflect the operation of the machine, and can also detect defective rotors (broken bars). In order to gain such model, an approach, that is based on modeling the machines rotor using kurchof law, this latter includes circuits with are attached to one another electrically and magnetically.

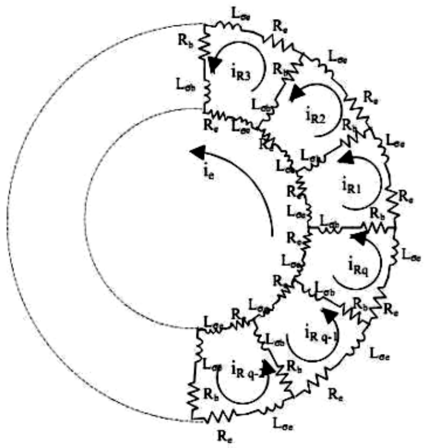

Figure.1 .Equivalent form of the Rotor cage

The mathematical model of the induction motor is shown as below:[7]

$$[L]\frac{d[I]}{dt}=[V]-[R][I] \qquad (1)$$

Where :

$$[L]=\begin{bmatrix} L_{sc} & 0 & -\frac{N_r}{2}M_{sr} & 0 & 0 \\ 0 & L_{sc} & 0 & -\frac{N_r}{2}M_{sr} & 0 \\ -\frac{3}{2}M_{sr} & 0 & L_{rc} & 0 & 0 \\ 0 & -\frac{3}{2}M_{sr} & 0 & L_{rc} & 0 \\ 0 & 0 & 0 & 0 & L_e \end{bmatrix}$$

$$[R]=\begin{bmatrix} R_s & -\omega L_{sc} & 0 & \frac{N_r}{2}\omega M_{sr} & 0 \\ \omega L_{sc} & R_s & \frac{N_r}{2}\omega M_{sr} & 0 & 0 \\ 0 & 0 & R_{rdd} & R_{rdq} & 0 \\ 0 & 0 & R_{rqd} & R_{rqq} & 0 \\ 0 & 0 & 0 & 0 & R_e \end{bmatrix}$$

The equation coming under, indicates, the application of summation when considering all faulty bars.

$$R_{rdd,rqq} = R_r + \frac{2}{N_r}(1-\cos\alpha)\sum_k R_{bfk}.(1\pm\cos(2k-1).\alpha) \qquad (2)$$

$$R_{rdq,rqd} = -\frac{2}{N_r}(1-\cos\alpha)\sum_k R_{bfk}.\sin(2k-1).\alpha \qquad (3)$$

R_{bfk} : additional resistance of defect of a rotor bar.

This expression is put to show the electromagnetic torques:

$$C_e = \frac{3}{2}p\left(\Phi_{ds}I_{qs} - \Phi_{qs}I_{ds}\right) \qquad (4)$$

The machine's tension expression comes as:[8][9]

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d\Phi_{ds}}{dt} - \omega_s \Phi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d\Phi_{qs}}{dt} + \omega_s \Phi_{ds} \\ 0 = R_r I_{dr} + \frac{d\Phi_{dr}}{dt} - \omega_r \Phi_{qr} \\ 0 = R_r I_{qr} + \frac{d\Phi_{qr}}{dt} + \omega_r \Phi_{dr} \end{cases} \qquad (5)$$

The *d* axis as oriented in correspondence with the axis of the rotor flux when applying field oriented control strategy:

$$\begin{cases} \Phi_{dr} = \Phi_r = \text{constant} \\ \Phi_{qr} = 0 \end{cases} \qquad (6)$$

When applying (4 and 6) results of the oriented control, these results are gotten :

$$C_e = \frac{3}{2}p.\frac{M}{L_{rc}}\Phi_r I_{qs} \qquad (7)$$

After, this the dynamic equation comes this way :

$$\begin{cases} V_{ds} = (R_s + s.\sigma.L_{sc})I_{ds} - \omega_s.\sigma.L_{sc}.I_{qs} \\ V_{qs} = (R_s + s.\sigma.L_{sc})I_{qs} + \omega_s \frac{M}{L_{rc}}\Phi_r + \omega_s.\sigma.L_{sc}.I_{ds} \end{cases} \qquad (8)$$

With: $\Phi_r = \frac{M}{1+sT_r}.I_{ds}$; $\omega_r = \frac{M}{T_r.\Phi_r}.I_{qs}$

III. SLIDING MODE CONTROL

The sliding mode control technique is developed from variable structure control (VSC) to solve the disadvantages of other designs of non-linear control systems.

Sliding mode control is based on two phases:[4][6]

- designing a discontinuous control low to oblige the system to move on the sliding surface in a fixed time.
- If the system is in ''sliding mode '', the system behavior does not get effected by any modeling uncertainties or problems.

The design of the control system will be illustrated for a non-linear system presented in the canonical form:[10]

$$\dot{X}(t) = f(x,t) + B(x,t)u(x,t) \qquad (9)$$

Where $x \in \Re^n$ is the state vector, $f(x,t) \in \Re^n$, $B(x,t) \in R^{n\times m}$ and $u \in R^m$ is the control vector.

From the system (9), it is possible for defining a set of the state trajectories like:

$$S = \{x(t); \sigma(x,t) = 0\} \qquad (10)$$

Where :

$$\sigma(x,t) = [\sigma_1(x,t), \sigma_2(x,t), ..., \sigma_n(x,t)]^T \qquad (11)$$

The switching control is planned, the state covergence to the sliding surface and kept on sliding manifold.

The error dynamics *e(t)* and their derivative $\dot{e}(t)$ are led to the origin through the sliding line.

$s_i(X) = 0$ is named a sliding surface, $s_i(X)$ is an $(n-1)$ dimensional switching function and is known as switching surface or switching hyper plane as indicated in figure (02).

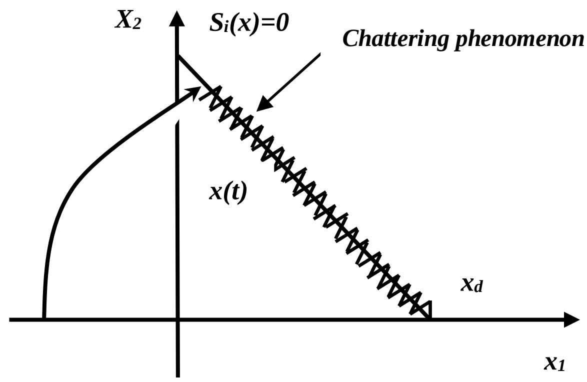

Figure.2 .The chattering Phenomenon near a sliding surface

The controlled input $u_i(X,t)$ is implemented to the system for gaining the wished output. The inouts of induction motor are (u_d, u_q), and the currents of induction motor (i_d, i_q) are needed to count for obtaining the willed speed ω.

Sliding surface can be described as:

$$s_i(x) = ce + \dot{e} \qquad (12)$$

Where

$$\dot{e} = \omega^* - \omega \qquad (13)$$

Here ω^* is the speed reference and c is a parameter designing and $c \succ 0$ that defined the error dynamics when the case reached to the sliding surface.

The controller $u_i(x,t)$ is divided to hitting control input and equivalent control

$$U_i(x,t) = u_{eq} - K.\text{sgn}(s) \quad (14)$$

K represents a positive constant.

The Sliding Mode must be well selected, in a way that the Lyapunov function satisfies the Lyapunov stability criteria:

$$\begin{cases} V(x) = \frac{1}{2}\sigma^2(x) \\ \dot{\sigma}(x).\sigma(x) \prec 0 \end{cases} \quad (15)$$

The well applied sliding surface was proposed by Slotine as:

$$S = \left(\frac{d}{dt} + \lambda\right)^{n-1} e \quad (16)$$

Where S is the sliding surface, λ is positive constant, e is the system error and n is the system relative order.

The control function will be satisfying, so that it reaches conditions in the following from:

$$U(t) = U_{eq} + U_n \quad (17)$$

$$U_n = -K.\text{sgn}(\sigma(x,t)) \quad (18)$$

Where U is the control vector, U_{eq} is the equivalent control vector, U_n is the correction vector, K is the controller gain, when the condition for the sliding regiment $\sigma(x,t) = 0$ is considered U_{eq} can be obtained. The state variable is kept on the sliding surface, when it is reached[11][12].

For defined signum function:

$$\text{sgn}(\varphi) = \begin{cases} 1 & \text{if } \varphi \succ 0 \\ 0 & \text{if } \varphi = 0 \\ -1 & \text{if } \varphi \prec 0 \end{cases} \quad (19)$$

The speed control block by the sliding mode control is shown in Figure 3.

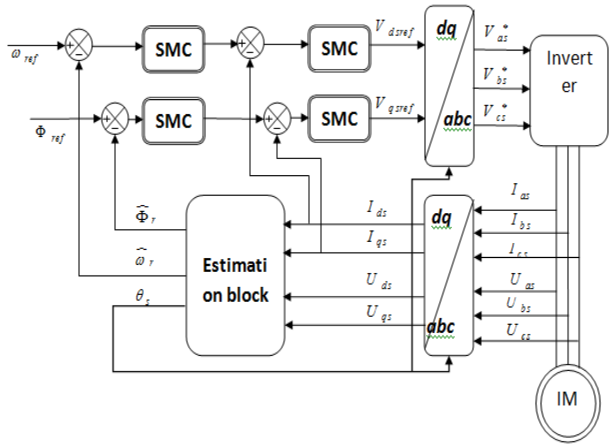

Figure.3. Blok diagram of sliding mode control.

IV. SIMULATION REESULTS

A. *Healthy case*

For analyzing the drive systems performance for speed and torque responses in state of healthy case, the following presented system has been simulated via the use of MATLAB/SIMILUNK software. The squirrel-cage of the tested induction motor consists of 16 bars, a speed reference 120 rad/s is imposed, t= 0.8s is applied on torque of 3.5Nm level, at time t=2s demine in speed at 100rad/s.

It is noted that the motor picks up the reference speed at t= 0.1s figure (4) explains the characteristics of the performance of the motor. The Sliding Mode Control controller shown good performance taking into consideration the rise time and the steady state error.

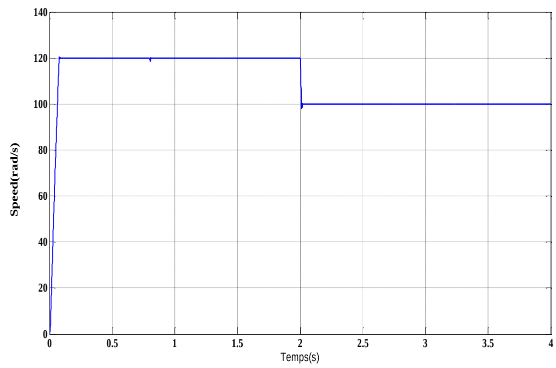

Figure 4.a: speed response

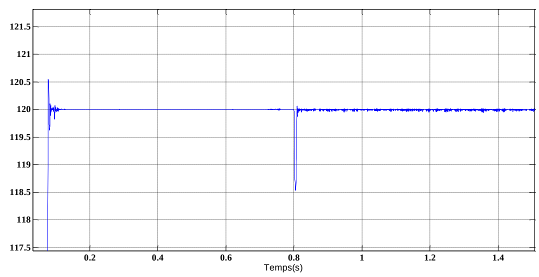

Figure 4.b: Zoom of Speed

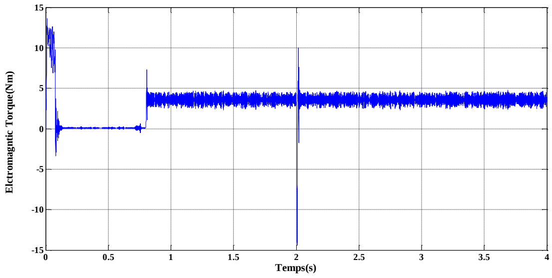

Figure 4.c:Torque for healthy motor

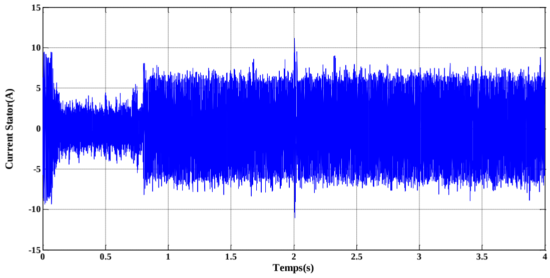

Figure 4.d: The stator current

Figure.4 .Simulation results with Sliding Mode controller

B. State of two broken bars

Figure (5) presents the simulation of the testing machine, the tested Induction Motors squirrel-cage is consisted of 16 bars, a speed reference of 120 rad/s is implemented, a 3.5 Nm torque level is put at t= 0.8s, at time t=2s decrease of speed at 100rad/s, we suggest a simulation of a first broken bar at t= 2.5s increasing resistance 11 times. The bar's resistance, the second adjacent broken rotor bars at t= 3s. During the bars break, a speed is noted to remain constant insensitive broken bars, showing the robustness of the order Sliding Mode Control.

A small fracture's stain of the bar is seen, (Figure 5.b) which deletes the loads instructions Sliding Mode Control influences perturbations applied at time t=0.8s, so we note also in the same Figure that the electromagnetic torque follows these instructions without making overflows at some considered moments and with less vibration, we may note an increase in the amplitude modulation of the stator current during the second broken rotor bar.

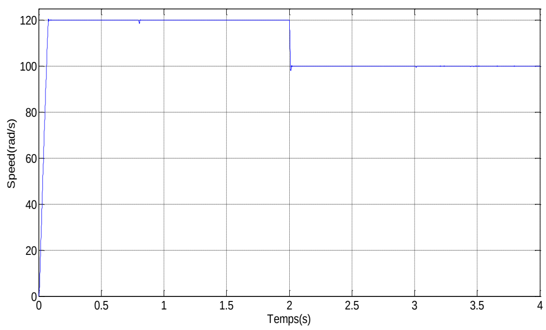

Figure 5.a: speed response

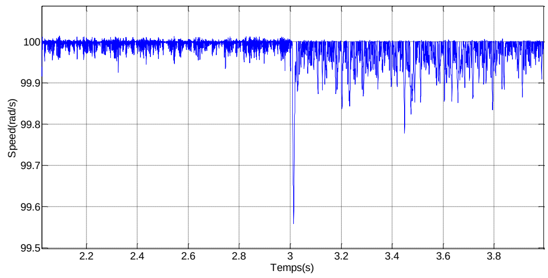

Figure 5.b: Zoom of speed

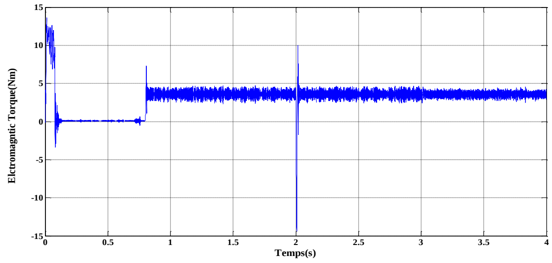

Figure 5.c: Torque for healthy motor and broken rotor bars N_0 1 and N_0 2

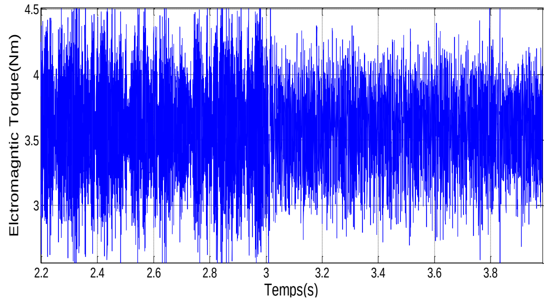

Figure 5.d: Zoom of Torque

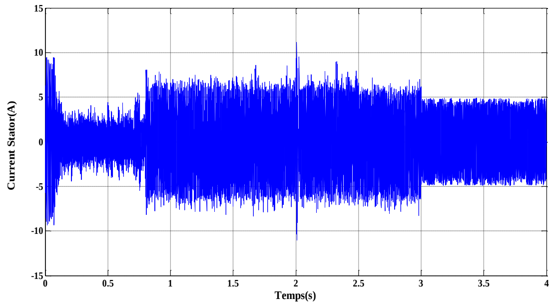

Figure 5.e: The stator current

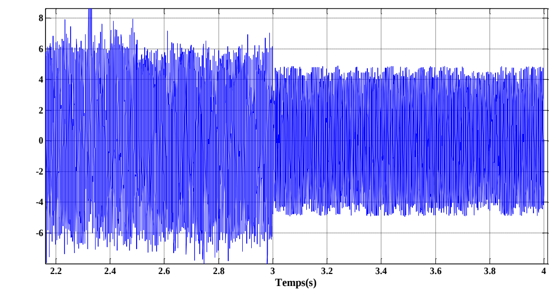

Figure 5.f: Zoom of stator current

Figure.5 .Simulation results without rotor defects.

DISCUSSION

The simulation results are discussed, and shown in this way: it is important to notice the degradation of the speed tracking with PI method in steady state after the fault occurrence, however when using the proposed controller of sliding mode controller rotor speed oscillations are hidden(check fig 5.a), on the other hand sliding mode controller reduces the torque oscillation considerably , it can be seen from these simulation results, that the sliding mode controller guarantees satisfactory robustness against the broken bars, while the PI is not able to master the unbalanced machine properly, in addition to all the previous mentioned, the tracing errors converge quickly and the robust control characteristics of the sliding mode controller system under the occurrence of uncertainties are clearly Observed. Finally, the influence of the broken bars is less effecting in sliding mode controller being compared to the PI controller.

CONCLUSION

This paper presented an analysis of sliding mode control of induction motor drive with the broken rotor bars faults.

Sliding mode control utilizes non linear properties, and it does not depend on the increased robustness to parameter variation only, but on the replacement of the traditional PI controller with sliding mode ones.

The simulation results show the reduction of sensitivity to parameters variations disturbances, and that it would give better performance when it is applied on induction motors with faulty state (broken bars), and it guarantees zero steady-state speed error.

APPENDIX

Resistance of stator and rotor R_s=7.58Ω, R_r=6.3Ω	50(Hz) Stator frequency
N_s=160 Number of turns per stator phase	N_r=16 Number of rotor bars
J=0.0054(Kgm^2) Inertia	p=2 Poles number
R_b=0.00015(Ω) Resistance of a rotor bar	R_e=0.00015 (Ω) Resistance of end ring segment
L_e=0.1e-6(H) Leakage inductance of end ring	L_b= 0.1e-6H Rotor bar inductance
L=65(mm) Length of the rotor	E=25(mm) Air-gap mean diameter
L_{1s}=0.0265(H) Mutual inductance	P=1.1(Kw) Output power
K_{id}=K_{iq}=34 Control gain	K_v=Kf=0.2869 Control gain

REFERENCES

[1] 1 Utkin V.I, “Variable structure systems with sliding modes” IEEE Trans. Autom. Control, Vol. AC-22, No. 2, pp, 212- 222, Apr, 1977.

[2] A, Soualhi, G. Clerc, H. Razik, “ Detection and Diagnosis of Faults in Induction Motor Using an Improved Artificial Ant Clustering Technique”, IEEE Transaction on Industrial Electronics, Vol. 60, no 9, September 2013.

[3] Yong F, Minghao Z, Xuemei Z, Fengling H, Xinghuo Y” Terminal Sliding Mode Control of Induction Motor Speed Servo Systems”, IEEE 2016

[4] Ghada K. Gameel, Fayez F. Areed, Mahmoud E. Abdalla” Sliding Mode Control for speed of an Induction Motor with Backlash” International Journal of Applications 0975- 8887, Vol 125-No 6, 2015.

[5] Xinghuo Yu, Kaynak, O” Sliding Mode Control With Soft Computing: A Survey” industrial electronics, IEEE Transactions on Vol . 56, Issue 9, july 2009.

[6] F Cipertino, A Lattanzi, L Salvatore “ Sliding Mode Control of an Induction Motor “ power Electronics and Variable speed Drives, conference publication No. 475, IEE 2000

[7] A.Menacer, R. Kechida, G. Champenois, S. Tnani, “ Application of the Fourier and the Wavelet Transform for the Fault Detection in Induction Motors at the Startup Electromagnetic Torque“ *Diagnostics for Electric Machines, Power Electrinics & Drives (SDEMPED),2011 IEEE International Symposium on.*

[8] Belhamdi S, Goléa A “Direct Torque Control for Induction Motor with broken bars Using Fuzzy Logic Type-2“, AMSE Journals, Advances C, vol. 70, no.1-2, pp.15-28, 2015.

[9] Belhamdi, S, Goléa, A “ Direct Field-Oriented Control Using Fuzzy Logic Type-2 for Induction Motor with broken bars”, AMSE Journals, Advances C, vol. 72, no.4, pp.203-212, 2017.

[10] R. S. Kumar, K. V. Kumar, K. K. Ray, “ Sliding Mode Control of Induction Motor using Simulation Approach” , IJCSNS Vol. 9 No. 10, October 2009.

[11] Belhamdi, S, Goléa, A,” Fuzzy logic Control of Asynchronous Machine Presenting Defective Rotor Bars”, AMSE Journals, Advances C, vol. 68, no. 2, pp. 54-63, 2013.

[12] Belhamdi, S, Goléa, A “ Fuzzy Sliding Mode speed controller Design of Induction Motor Drives with broken bars”, AMSE Journals, Advances C, vol.72, no.4, pp.281-291, 2017.