AMSE JOURNALS-AMSE IIETA publication-2017-Series: Advances C; Vol. 72; N°4; pp 281-291
Submitted July 2017; Revised Oct. 30, 2017, Accepted Nov.15, 2017
https://doi.org/10.18280/ama_c.720406

Fuzzy Sliding Mode Speed Controller Design of Induction Motor Drives with Broken Bars

Belhamdi Saad *, Amar.Goléa **

* Electrical Engineering Laboratory, LGE, University of M'Sila, Algeria (bsaad1@yahoo.fr)
**LGEB Laboratory, University of Biskra, Algeria

Abstract

Because of the low maintenance and robustness induction motors have many applications in the industries. Fuzzy Sliding Mode Controller (FSMC) is designed for the speed loop of the drive with broken bar. The motor model is designed and membership functions are chosen according to the parameters of the motor model. The simulated design is tested using various tool boxes in MATLAB. The result concludes that the efficiency and reliability of the proposed speed controller is good.

Keywords

Induction motor, Sliding Mode, FSMC, Membership function, Rotor fault.

1. Introduction

Induction motors fulfill the de facto industrial standard, because of their simple and robust structure, higher torque-to-weight ratio, higher reliability and ability to operate in hazardous environment. However, because of the coupling between torque and flux, unlike dc motor, their control is a challenging task. (Vinod Kumar, R. R. Joshi 2006 and Belhamdi, S, Goléa, A 2014). In this sense, there are many studies focused on early fault detection. In this manner, over the past 30 years, several artificial intelligence techniques have been developed and applied in the monitoring processes of faults, among them, the Artificial Neural Networks (ANNs), Fuzzy Logic (FL) (H. Hagras 2007 and Vinod Kumar, R. R. Joshi 2006). A sliding mode speed controller, based on a switching surface, is demonstrated. With this switching surface, the stability is guaranteed for the speed control, and insensitivity to uncertainties and disturbances is also obtained. (M W Dunnigan, S Wade, B W Williams and X Xu 1998). This paper deals with fuzzy based fault detection and control of an induction motor.

Fuzzy logic is a technique to embody human-like thinking into a control system. A fuzzy controller can be designed to emulate human deductive thinking, that is, the process people use to infer conclusions from what they know. Fuzzy control has been primarily applied to the control of processes through fuzzy linguistic descriptions. Fuzzy control system consists of four blocks as shown in Fig. 2. (H. Hagras 2007 and Ashok Kusagur, 2009). The rest of the paper is divided into five sections. The induction motor modeling is dealt in Section II. Section III describes the sliding mode controller. The fuzzy controller design is presented in Section IV. In Section V the fault diagnosis concept and its simulation using fuzzy sliding mode controller is explained. Conclusion and reference studies are mentioned in the last section.

2. Modeling the induction motor for its control

The induction motor has the advantage of being robust, inexpensive and simple construction. This simplicity, however, comes great physical complexity related to electromagnetic interaction between the stator and the rotor . Moreover, to develop control approaches ensuring the hoped performance, we need a model that reflects the operation of the machine so that transient steady, and a model to account for failures rotor (Belhamdi, S, Goléa, A 2013).

The electromagnetic torque is found as:

$$C_e = \frac{3}{2} p.\left(\Phi_{ds}.I_{qs} - \Phi_{qs}.I_{ds}\right) \tag{1}$$

The equations tension of the machine is written to the system related to the rotating field configuration as follows (Belhamdi, S, Goléa, A 2015):

$$\begin{cases} V_{ds} = R_s.I_{ds} + \dfrac{d\Phi_{ds}}{dt} - \omega_s \Phi_{qs} \\ V_{qs} = R_s.I_{qs} + \dfrac{d\Phi_{qs}}{dt} + \omega_s \Phi_{ds} \\ 0 = R_r.I_{dr} + \dfrac{d\Phi_{dr}}{dt} - \omega_r \Phi_{qr} \\ 0 = R_r.I_{qr} + \dfrac{d\Phi_{qr}}{dt} + \omega_r \Phi_{dr} \end{cases} \tag{2}$$

The main objective of the vector control of induction motors is, as in DC machines, to independently control the torque and the flux; this is done by using a d-q rotating reference frame synchronously with the rotor flux space vector . In ideally field-oriented control, the rotor flux linkage axis is forced to align with the d-axes, and it follows that (Vinod Kumar, R. R. Joshi 2006).

$$\begin{cases} \Phi_{dr} = \Phi_r = \text{constant} \\ \Phi_{qr} = 0 \end{cases} \tag{3}$$

Applying the result of (3) and (4), namely field-oriented control, the torque equation becomes analogous to the DC machine and can be described as follows:

$$C_e = \frac{3}{2} p \cdot \frac{M}{L_{rc}} \Phi_r I_{qs} \tag{4}$$

Consequently, the dynamic equations (2) yield:

$$\begin{aligned} V_{ds} &= \left(R_s + s.\sigma \cdot L_{sc}\right) I_{ds} - \omega_s.\sigma \cdot L_{sc}.I_{qs} \qquad & \Phi_r &= \frac{M}{1 + sT_r} I_{ds} \\ V_{qs} &= \left(R_s + s.\sigma \cdot L_{sc}\right) I_{qs} + \omega_s \frac{M}{L_{rc}} \Phi_r + \omega_s \sigma.L_{sc}.I_{ds} \qquad & \omega_r &= \frac{M}{T_r \Phi_r} I_{qs} \end{aligned} \tag{5}$$

3. Sliding mode controller

A Sliding Mode Controller (SMC) is a Variable Structure Controller (VSC). Basically, a VSC includes several different continuous functions that can map plant state to a control surface, whereas switching among different functions is determined by plant state represented by a switching function. The design of the control system will be demonstrated for a following nonlinear system (Utkin 1993 and M W Dunnigan, S Wade, B W Williams and X Xu 1998):

$$\dot{x} = f(x,t) + B(x,t).u(x,t) \tag{6}$$

Where $x \in \Re^n$ is the state vector, $f(x,t) \in \Re^n$, $B(x,t) \in \Re^{n \times m}$ and $u \in \Re^m$ is the control vector. From the system 6, it possible to define a set of the state trajectories x such as:

$$S = \{x(t)|\sigma(x,t) = 0\} \quad (7)$$

Where:

$$\sigma(x,t) = [\sigma_1(x,t), \sigma_2(x,t), ..., \sigma_m(x,t)]^T \quad (8)$$

And $[.]^T$ denotes the transposed vector, S is called the sliding surface. To bring the state variable to the sliding surfaces, the following two conditions have to be satisfied:

$$\sigma(x,t) = 0, \dot{\sigma}(x,t) = 0 \quad (9)$$

The control law satisfies the precedent conditions is presented in the following form:

$$U(t) = U_{eq} + U_n \quad (10)$$

$$U_n = -k.\operatorname{sgn}(\sigma(x,t)) \quad (11)$$

Where U is the control vector, U_{eq} is the equivalent control vector, U_n is the switching part of the control (the correction factor), k is the controller gain. U_{eq} can be obtained by considering the condition for the sliding regimen, σ(x, t) = 0. The equivalent control keeps the state variable on sliding surface, once they reach it. (Belhamdi, S, Goléa, A 2011):

For a defined function φ:

$$\operatorname{sgn}(\varphi) = \begin{cases} 1, & if \quad \varphi \succ 0 \\ 0, & if \quad \varphi = 0 \\ -1, & if \quad \varphi \prec 0 \end{cases} \quad (12)$$

Consider a Lyapunov function:

$$V = \frac{1}{2}\sigma^2 \quad (13)$$

So that the function of Lyapunov decreases, it is enough to ensure that its derivative is negative. This is checked if:

$$S(x).\dot{S}(x) \prec 0 \tag{14}$$

Synthesis of the law of order to variable structure for control speed

The nonlinear adjustment by mode of slip uses the principle of the method of adjustment in cascade. The synthesis of order exploits the technique of the sliding modes. The latter requires the choice of surfaces which ensures the objectives of order (Belhamdi, S, Goléa, A 2011):

Speed regulation

As the continuation speed is imposed by the order of I^*_q and that surface $S(\Omega)$ must be relative degree of order 1, then the error of adjustment is selected like surface:

$$S(\Omega) = \Omega_{ref} - \Omega \tag{15}$$

Its derivative is given by:

$$\dot{S}(\Omega) = -c_1\Omega + \frac{C_r}{J} + \dot{\Omega}_{ref} - (c_2 I_d + c_3) I_q \tag{16}$$

Where $\dot{\Omega}_{ref}$ indicate the temporal derivative of the reference speed. The exit of the speed regulator will be thus:

$$I_{qref} = \frac{-c_1\Omega + \frac{C_r}{J} + \dot{\Omega}_{ref}}{(c_2 I_d + c_3)} + K_1 Sign S(\Omega) \tag{17}$$

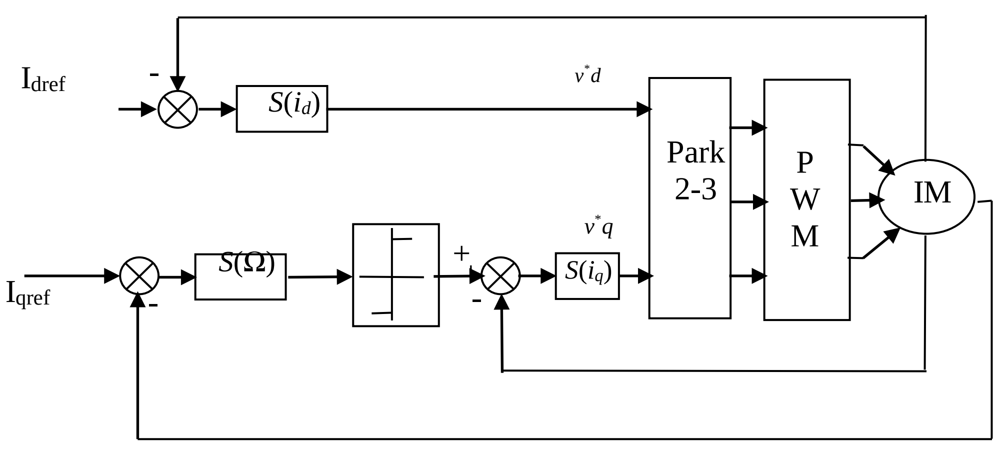


Figure .1 Structure of speed ordering for the induction motor

4. Design of fuzzy sliding mode controller

After Zadeh presented the fuzzy sets, the concepts of fuzzy algorithms, fuzzy decision making, and fuzzy ordering had been proposed. In 1973, Zadeh published another paper which established the foundation for fuzzy control. In that paper he introduced the concept of linguistic variables and proposed the IF-THEN rules to formulate human knowledge (S. Drid. and all 2007. A. M. Harb, I. Al-Smadi 2007).

The fuzzy sliding mode controller (FSMC) explained here is a modification of the sliding mode controller equations (10), where the switching controller term, - K × sgn (φ), has been replaced by a fuzzy control input as:

$$U = U_{eq} + U_{fuzzy} \tag{18}$$

$$U_{fuzzy} = -K_{fuzzy}.\text{sgn}(\varphi) \tag{19}$$

The gain, K_{Fuzz} of the controller is determined from fuzzy rules.

Principe of a fuzzy controller

The control by fuzzy logic permits to obtain a law of drive, often very effective, without having a precise model of the process, from a linguistic description of the behavior of the system. Its approach is different the one of the automatic classic, in the sense that it does not treat mathematical relations well defined, but it exploits the knowledge of an expert. These are expressed by means of conduct rules based on a symbolic vocabulary and manipulate inferences with several rules using the fuzzy operators AND, OR, THEN, applied to linguistic variables. (Belhamdi, S, Goléa, A 2011).

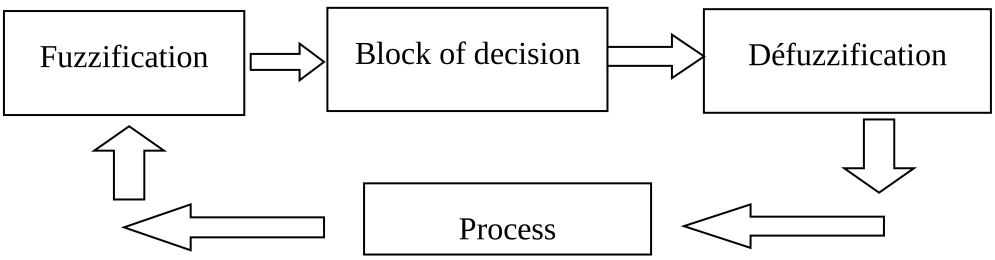


Figure 2. structure interns of a system Fuzzy

The block diagram of the hybrid fuzzy sliding mode controller is shown in Figure. 3.

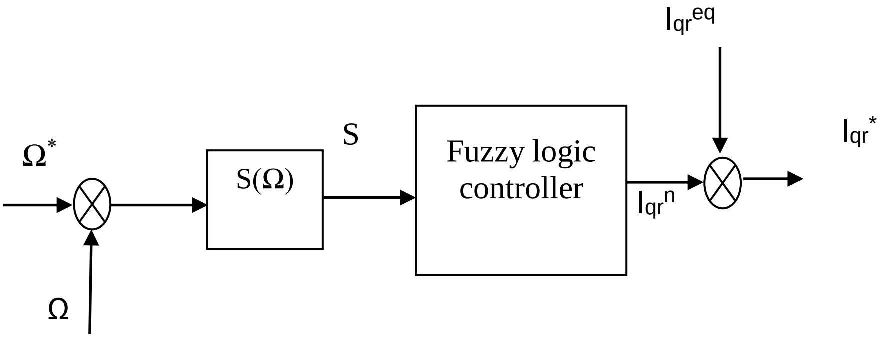


Figure 3. Fuzzy sliding mode speed controller

A relation between input linguistic variables and output linguistic variable is determined by 25 fuzzy rules. (Belhamdi, S, Goléa, A 2015).

Table 1. Fuzzy rule for type-1 FLCS

		e				
		NB	**N**	**Z**	**P**	**PB**
De	**NB**	NB	NB	N	N	Z
	N	NB	N	N	Z	PB
	Z	N	N	Z	P	PB
	P	N	Z	P	P	PB
	PB	Z	P	P	PB	PB

Table 1 show the linguist rules used in the Fuzzy logic Controller. In these table, NB, N, Z, P, PB, represent negative big, negative, zero, positive and positive big, respectively.

5. Simulation Results

5.1. Simulation in healthy condition

To prove the rightness and effectiveness of the proposed control scheme, we apply the designed controllers to the speed control of the induction motor with broken bar. Figures 4 shows the speed response, torque, current stator and speed of fuzzy sliding mode controller when the machine is operated at 100 [rad/sec] under no load and a nominal load disturbance torque (3.5 N.m) is suddenly applied at 0.8sec. The control objective is to ensure that actual output follows the reference with minimum steady-state error. The response shows how the command torque matches perfectly the motor torque at steady state. The FSMC presents the best performances, to achieve tracking of the desired trajectory.

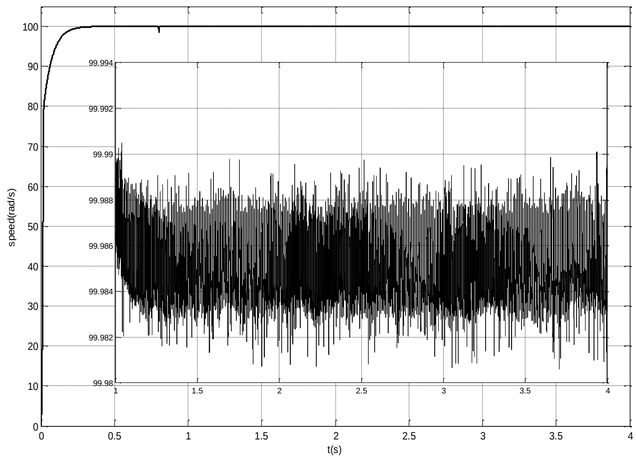


Fig. 4.a: Speed response

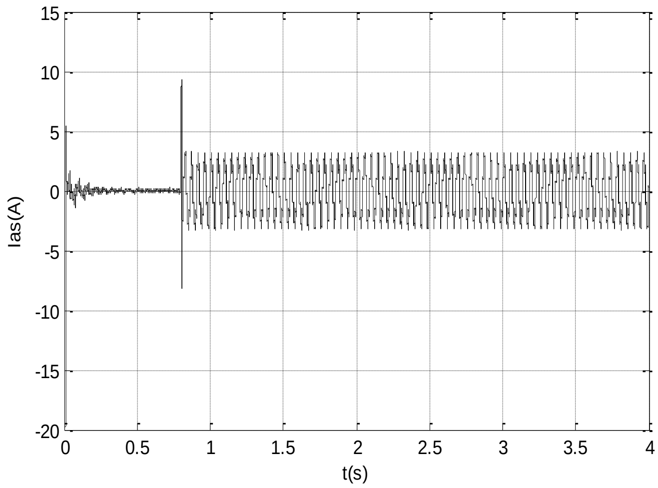


Fig.4.b: The Stator current

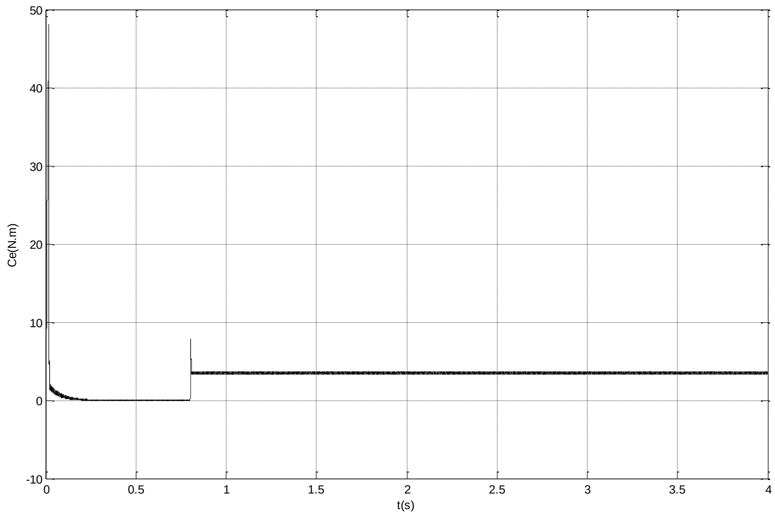


Fig. 4.c: Torque for healthy motor

Figure 4. Simulation results without Small-scale model

5.2 Case of Two Broken bars

The main goal of this research was an analysis of the rotor fault influence on the control signals of the fuzzy sliding mode controller and determination of the fault signature visible in the chosen control signals. In the simulation tests a simplified mathematical model of the induction motor with broken rotor bars was used. Each rotor fault was modeled as a full broken rotor bar. The squirrel-cage rotor of the tested IM consists of 16 bars. At t=2s we simulate a first broken bar, this is achieved by increasing its resistance, we only notice small oscillations on the speed. The second bar is broken a t=3s. We notice the appearance of fluctuations on the shapes of the torque. Speed remains always not very disturbed by this defect. For current I have one sees well a deformation during the rupture of the second bars. An analysis of these internal signals of the closed-loop control structure makes possible a choice of the most suitable ones for fault signature detection, It was concluded that the most informative signals are: torque component of the stator current, decoupling signals, as it is shown in Figure.5. The figures show that the proposed controller gave satisfactory performances thus judges that the controller is robust.

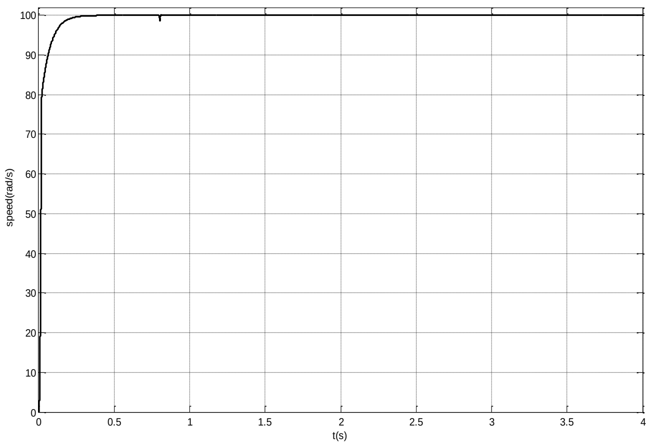
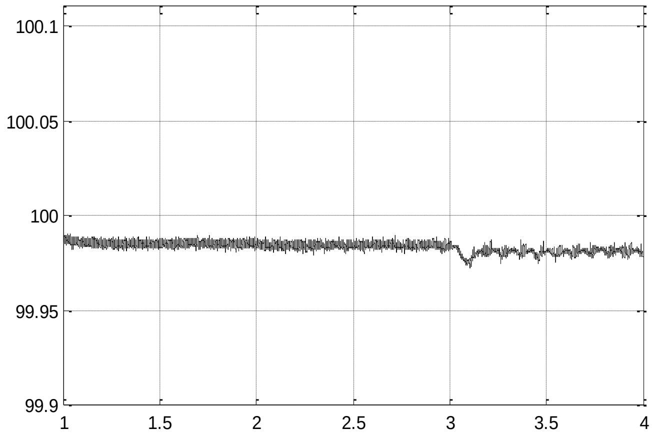


Fig. 5.a: Speed response



Zoom for the speed

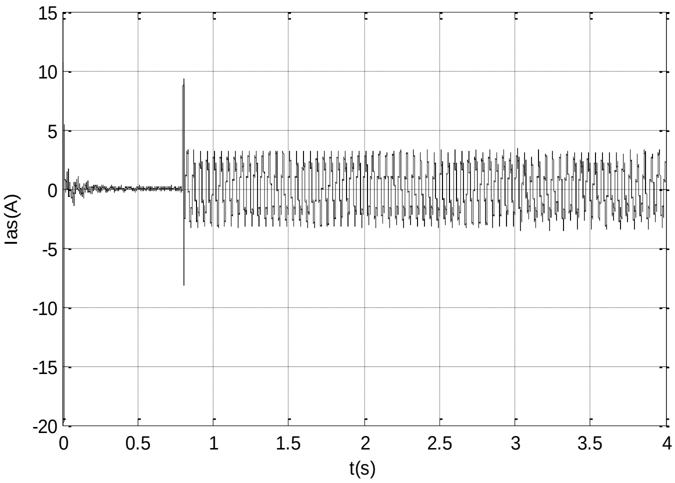
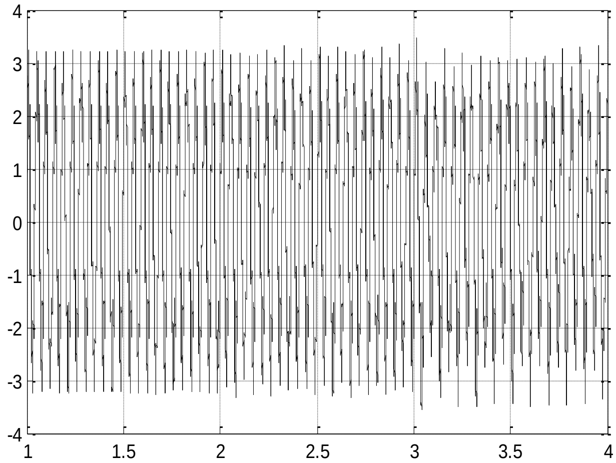


Fig. 5.b: The Stator current



Zoom of stator current

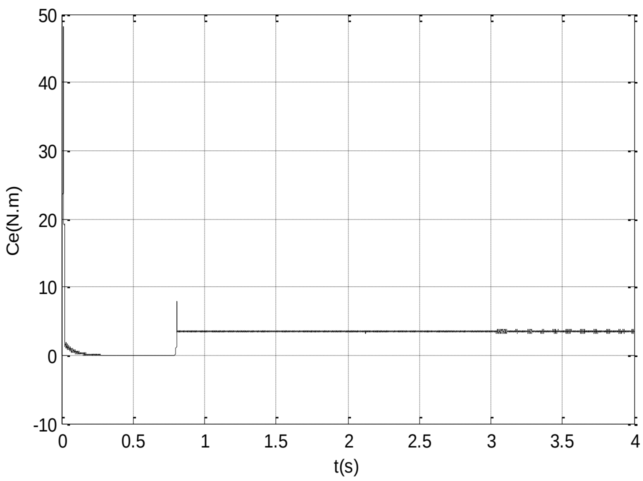
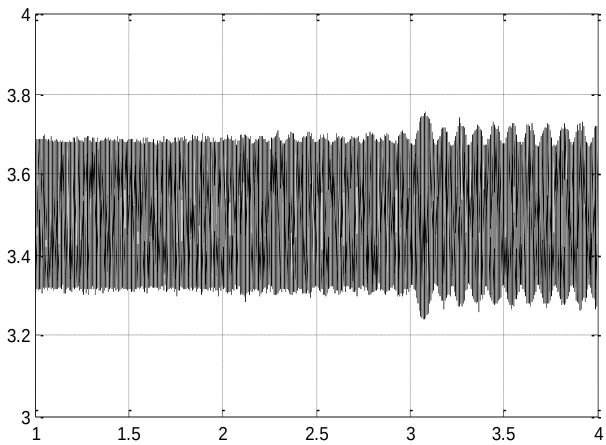


Fig. 5.c: Torque for healthy motor and broken bar No 1 and 2



zoom for the torque

Figure 5. Simulation results without rotor defects

6. Conclusion

A fuzzy sliding mode control scheme was proposed in this paper for an induction motor speed control to reduce the sensitivity to parameter variations disturbances; in the control scheme, the establishment of the control rule was based on a systematic procedure.

Fuzzy sliding mode controllers are designed for afield oriented induction motor drive, whereas these are free of chattering with fuzzy sliding mode controller.

The number of members in the input and output sets of the fuzzy controller can be increased, so also the number of rules in the fuzzy rule base, so as to closely approximate the linear transfer characteristics within the boundary layer. This would give better performance of the controller at the cost of increased computational time. Our future work is to apply type-2 fuzzy sliding mode control FSMC to an induction motor with broken bar.

References

1. S. Belhamdi, A. Goléa, Direct Torque Control for Induction Motor with broken bars Using Fuzzy Logic Type-2AMSE Journals, Advances C, vol. 70, no. 1-2, pp. 15-28, 2015.
2. H. Hagras. Type-2 FLCs, A new generation of fuzzy controllers, IEEE Computational Intelligence Magazine, vol. 2, pp. 30-43, 2007.
3. Vinod Kumar, R. R. Joshi, Hybrid Controller based Intelligent Speed Control of Induction Motor, Journal of Theoretical and Applied Information Technology, vol. 3, no. 1, pp. 71- 75, 2006.
4. S. Belhamdi, A. Goléa, Fuzzy logic Control of Asynchronous Machine Presenting Defective Rotor Bars, Association for the advancement of modeling & Simulation techniques in Enterprises, advancement of modelling C, vol. 68, no. 2, pp. 54-63, 2013.
5. M. W. Dunnigan, S. Wade, B. W. Williams and X. Xu. Position Control of a Vector Controlled Induction Machine Using Slotine's Sliding Mode Control Approach. IEE Proceedings of Elect Power Appl, vol. 145, no 3, pp. 231-238, May 1998.
6. Ashok Kusagur, F. Kodad, B.V. Sankar Ram, Al based design of a fuzzy logic scheme for speed control of induction motors using SVPWM technique, Proc, Int. Jr. Comp. Sci & Network Security, vol. 9, no. 1, pp. 74-80, 2009.
7. V. I. Utkin, Sliding Mode Control Design Principles and Applications to Electric Drives, IEEE Trans. Ind. Electr., vol. 40, no. 01, pp. 23-36, 1993.
8. S. Belhamdi, A. Goléa, Sliding Mode Control of Asynchronous Machine Presenting Defective Rotor Bars, Association for the advancement of modeling & Simulation techniques in Enterprises, advances in Modelling C, vol. 66, no. 1-2, pp. 39-49, Issue 2011.

9. S. Drid, M. Tadjine and M. S. Naît-Saîd, Robust backstepping vector control for the doubly fed induction motor, The Institution of Engineering and Technology, Control Theory Appl., vol. 1, no. 4, pp. 861–868, 2007.
10. A. M. Harb, I. Al-Smadi, Chaos Control Using Fuzzy Controllers, Integration of Fuzzy Logic and Chaos Theory, Springer Berlin Heidelberg, vol. 187, pp. 127-155, 2006.

Appendix

The parameters of the machine used for simulation are listed below (Belhamdi, S, Goléa, A 2015):

R_s=7.58(Ω) Stator resistance

R_r=6.3(Ω) Rotor resistance

J=0.0054(Kgm^2) Inertia

N_s=160 Number of turns per stator phase

N_r=16 Number of rotor bars

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

p=2 Poles number

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

K0=0 (SI) Friction coefficient

220/380(V) Stator voltage

50(Hz) Stator frequency