Periodica Polytechnica
Transportation Engineering

44(3), pp. 172-180, 2016
DOI: 10.3311/PPtr.8242
Creative Commons Attribution

RESEARCH ARTICLE

Hybrid Control Using Adaptive Fuzzy Sliding Mode for Diagnosis of Stator Fault in PMSM

Amar Bechkaoui[1*], Aissa Ameur[2], Slimane Bouras[1], Kahina Ouamrane[1]

Received 13 May 2015; accepted 08 February 2016

Abstract
In nonlinear control systems when we have a non-constant parameters, conventional control laws may be insufficient because they are not robust especially when the requirement on accuracy and other characteristics dynamic systems are strict. We must use control laws insensitive against to parameter variations, disturbance and nonlinearities. For this purpose, several tools are proposed in the literature, which is quoted a hybrid fuzzy logic and variable structure control (Fl_VSC). This per presents an application of the fuzzy logic scheme to control the speed of PMSM by taking account of the presence of inter-turn short circuit fault. We were interested in the sliding mode control (SMC) of the PMSM using controller's fuzzy logic controller (FLC) and Adaptive fuzzy logic controller (AFLC). The combination of these two theories has given great performance with fast dynamic response without overshoot. As it has a very robust control, insensitive against to parameters variation and external disturbances. Simulation results confirm the choice of hybrid controllers compared with the conventional controllers and grants a robust performance and precise response to the reference model regardless of load disturbance, stator faults and PMSM parameter uncertainties.

Keywords
diagnosis, inter-turn fault, PMSM, sliding mode control, fuzzy logic controller

[1] Electromechanical Engineering Department, University Badji Moukhtar Sidi Amar, Annaba, B.P.12, Algeria

[2] Electrical Engineering Department, University Amar Telidji, Laghouate, B.P. 37, Algeria

[*] Corresponding author, e-mail: amaramour73@yahoo.com

1 Introduction

Permanent magnet synchronous motors (PMSM) become more attractive and competitive than asynchronous motors thanks to many reasons such as the components technology development of the power electronics and the apparition of digital processors in high frequency and high computing power (Ameur et al., 2013).

In addition, technology evolves with the rare earth bonded magnet and rare earth-iron-boron type magnet alloy. It is especially the rare earth (samarium-cobalt and neodymium-iron-boron) that are more effective. This allowed them to be used as an inductor in synchronous machine offering many advantages, among others, low inertia, high power density and efficiency and low-consumption (Ameur et al., 2010).

Conventional PI controllers and feedback control widely used control strategy are insufficient to meet the required performance. They are subject to deterioration in the presence of the disturbance load performance and parametric variations (Masumpoor et al., 2015). To overcome this problem, the use of intelligent controls become more necessary especially whose its mathematical model is difficulty or not to define (Masumpoor et al., 2015; Ameur et al., 2013b). Following the appearance of fuzzy logic processors, this controls strategy has been successfully applied in the control of many industrial processes. Therefore, algorithms based on fuzzy logic are regarded as a very interesting solution for nonlinear control systems or systems which has no mathematical models (Ameur et al., 2013). Their main purpose is to implement a human expert knowledge (or heuristics), in the form of a computer program. Electric machines including synchronous machines have a non-linear dynamic which makes the conventional control ineffective and justified the use of fuzzy logic.

Sliding mode observers (SMO) provide an effective way of improving the robustness of the control system against parameter variation, load disturbance and measurement errors due to its simple structure and fast response. Sliding mode control has been successfully employed to nonlinear control problems (Ameur et al., 2010). Their implementation to electromagnetic machine is a special case. This technical has undergone significant developments in all areas of the control. It consists in bringing the status path to the sliding area and to switch by means clustering of a switching logic sliding around the lath up to it is balanced or of the sliding phenomenon. This makes the system insensitive to curly some parametric variations and disturbances (Bessa and Barrêto, 2010; Wang, 1993).

SMC method has many advantages; there still exist some drawbacks such as the phenomenon of chattering and the steady state error. One approach for chattering reduction involves introducing a boundary layer. Therefore we use the saturation function to replace the sign function. The saturation function can be smooth in the controller and eliminate the phenomenon of chattering (Cheng et al., 2011; Tseng and Chen, 2010).

Recently, much effort has been made to combine fuzzy logic with nonlinear control methodology (Bessa and Barrêto, 2010). Therefore, hybrid combinations of the SMC, fuzzy logic, and adaptive control can be an attractive alternative for designing robust control systems with high degrees of non-linearity and uncertainties. In (Wang, 1993) a globally stable adaptive fuzzy controller was proposed using Lyapunov stability theory to develop the adaptive law.

In some applications, the PMSM fault detection is one of the most important issues due to the safety and high fault time cost. One common fault of the PMSM is a winding turn short fault caused by the coil insulation failure (Choi et al., 2013; Vaseghi et al., 2011).

In this paper, a comparative study of two types of controllers FLC and AFLC associated with the SMC control dedicated to fault diagnosis of an inter-turn short circuit. This comparison reveals which of the two controllers is the most robust for the motor control and faults diagnosis. Tests regarding these two controllers associated with the sliding mode control were carried out on a PMSM 5KW exposed to different loads and a reversed rotation direction for a functioning in healthy and degraded state due to a different number of inter-turn short circuits. The effectiveness and validity of the proposed control approach is verified by simulation results. Rest of the paper organized as follows: In Section 2, the modelling of the PMSM with inter-turns fault is presented. The theory of sliding mode control is given in Section 3. Section 4, we define the model of a adaptive fuzzy. Simulation results with conventional fuzzy logic controller and adaptive fuzzy logic controller are presented in Section 5. Finally the conclusion presented in Section 6.

2 Model of the PMSM with inter-turns fault

2.1 Fault model in abc coordinates

In this section the model of a healthy and faulty PMSM with stator winding inter-turn fault is derived. Modeling of PMSM operating under this type of fault is the first stage to understand their effects in PMSM drive. Several models have been created to describe an AC machine with inter-turn short-circuit faults (Farooq et al., 2008; Tallam et al., 2000) but they do not take into account the effects of spatial harmonics.

In the case of an inter-turn short-circuit fault, both the actual speed of the PMSM and the ratio $\mu = N_{cc}/\mathrm{N}$, between the number n short-circuited inter-turns and the total number of turns N in a certain phase, greatly affects the severity of the fault. The current through the n short-circuited turns is designated as if while rf is a resistance whose value depends on the fault severity. Lower values of rf indicate severest inter-turn short-circuit conditions.

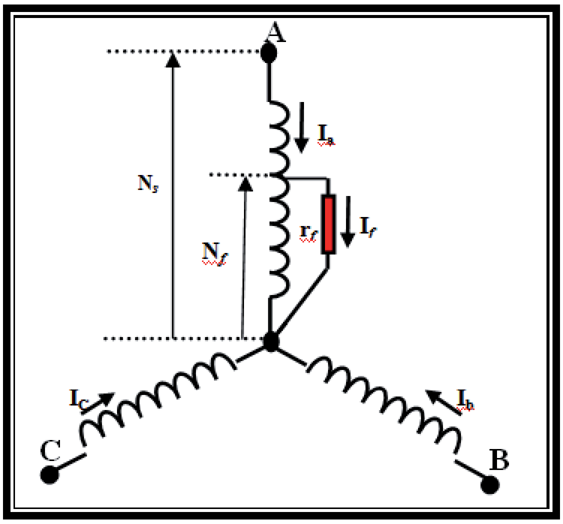

Fig. 1 Three phase stator winding with turn fault in Phase “a”.

According to Fig. 1, the voltage equation is expressed by:

$$\begin{aligned}[V_s] &= R_s[I_s] + L\frac{d[I_s]}{dt} + [E_s] - N_{cc}R_sT_{s/c}I_f \\ &-\sqrt{\frac{3}{2}}N_{cc}L_{ps}T_{32}\begin{bmatrix}\cos(\theta_{cc})\\ \sin(\theta_{cc})\end{bmatrix}\frac{d[I_f]}{dt} \\ &-N_{cc}L_sT_{s/c}\frac{d[I_f]}{dt}\end{aligned} \quad (1)$$

Where:

θ_{cc}: equal to 0, 2π/3 or 4π/3 for a short-circuit respectively on phase A, phase B or phase C.

$[V_s]$, $[I_s]$ and $[E_s]$ are the stator voltage, current and electromotive forces vector:

$$[V_s] = [v_{as} \quad v_{bs} \quad v_{cs}]^T$$

$$[I_s] = [i_{as} \quad i_{bs} \quad i_{cs}]^T$$

$$[E_s] = [e_{as} \quad e_{bs} \quad e_{cs}]^T$$

R_s is the phase resistance and [L] is the inductance matrix of the healthy PMSM respectively.

$$[\mathrm{L}] = \begin{bmatrix} L_{ls}+L_{ps} & \frac{-L_{ps}}{2} & \frac{-L_{ps}}{2} \\ \frac{-L_{ps}}{2} & L_{ls}+L_{ps} & \frac{-L_{ps}}{2} \\ \frac{-L_{ps}}{2} & \frac{-L_{ps}}{2} & L_{ls}+L_{ps}\end{bmatrix}$$

Where:

$L_s = \frac{3}{2} L_{ps} + L_{ls}$ stator synchronous inductance.

The equation of the short-circuits fault party (a_{s2}) is:

$$\begin{aligned} 0 &= N_{cc} R_s T_{s/c}{}^{T} [I_s] + \sqrt{\frac{3}{2}} N_{cc} L_{ps} \left(T_{32} \begin{bmatrix} \cos(\theta_{cc}) \\ \sin(\theta_{cc}) \end{bmatrix} \right)^{T} \frac{d[I_s]}{dt} \\ &- N_{cc} T_{s/c}{}^{T} [E] + N_{cc} R_s I_f \end{aligned} \tag{2}$$

$$[T_{s/c}] = \frac{1}{3} \begin{bmatrix} 1 + 2\cos(\theta_{cc}) \\ 1 + 2\cos\left(\theta_{cc} - \frac{2\pi}{3}\right) \\ 1 + 2\cos\left(\theta_{cc} - \frac{2\pi}{3}\right) \end{bmatrix} \quad \text{short-circuit matrix}$$

$$\left(= \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \; if \; \theta_{cc} = 0; = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \; if \; \theta_{cc} = \frac{2\pi}{3}; = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \; if \; \theta_{cc} = \frac{4\pi}{3} \right)$$

The expression of the electromagnetic torque (T_e) and the mechanical equation are given as follows:

$$\begin{aligned} T_e &= \frac{[E_s]\,[I_s] - e_{a2} i_f}{\Omega} \\ T_e - T_l &= J \frac{d\Omega_r}{dt}. \end{aligned} \tag{3}$$

Where J is the moment of inertia and T_l is the load torque. Ω_r is the mechanical angular speed.

2.2 Fault model in d-q coordinates

With the Park transformation application to (1), the faulty model can be expressed as follow:

$$\begin{aligned} [V_s]_{dq} &= R_s [I'_s]_{dq} + wL_s \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} [I'_s]_{dq} + L_s [\dot{I}_s] + [E]_{dq} \\ [I_s]_{dq} &= [I'_s]_{dq} - [I'_f]_{dq} = [I'_s]_{dq} - \frac{1}{[Z_f]_{dq}} [V_s]_{dq} \end{aligned} \tag{4}$$

$$\frac{1}{[Z_f]_{dq}} = \frac{2N_{cc}}{(3 - 2N_{cc}) R_s} P(\theta)^T Q(\theta_{cc}) P(\theta)$$

Equivalent short-circuits fault impedance.

$$P(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \quad \text{Park transformation matrix.}$$

$$Q(\theta_{cc}) = \begin{bmatrix} \cos^2(\theta_{cc}) & \cos(\theta_{cc})\sin(\theta_{cc}) \\ \cos(\theta_{cc})\sin(\theta_{cc}) & \sin^2(\theta_{cc}) \end{bmatrix}$$

Fault localization matrix.

$$[\tilde{I}_f]_{dq} = P(\theta)^T \sqrt{\frac{2}{3}} N_{cc} \begin{bmatrix} \cos(\theta_{cc}) \\ \sin(\theta_{cc}) \end{bmatrix} I_f \quad \text{Short-circuit}$$

current calculation in dq frame.

$$[I'_s]_{dq} = [I_s]_{dq} + [\tilde{I}_f]_{dq} \quad \text{Stator current calculation in dq frame}$$

The Eq. (4) can be decomposed into a healthy machine part and the other appearing due to short circuit fault. The short-circuit current is represented by the equivalent fault impedance [Z_{cc}] at the output of the machine which deflects a part of the stator current. Expending this model to each phase, three short-circuit impedances (Z_{cc1}, Z_{cc2}, Z_{cc3} for $\theta_{cc} = 0, 2\pi/3, 4\pi/3$ respectively) are added to the PMSM model as shown on Fig. 2.

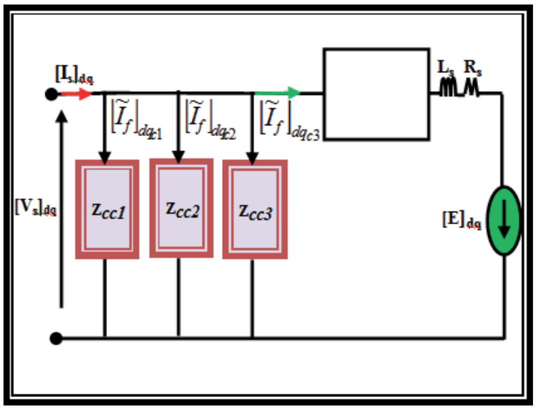

Fig. 2 Global inter-turn faulty PMSM model in Park's frame

3 Sliding Mode Controller

3.1 Principle of sliding mode controller

The sliding mode control is to bring the trajectory state and to evolve it on the sliding surface with a certain dynamic to the equilibrium point. As a result the sliding mode control is based on three steps (Ahmed et al., 2007).

3.1.1 Choice of the switching surface

J. Slotine proposes a form of general equation to determine the sliding surface (Slotine and li, 1998).

$$\begin{aligned} S(X) &= \left(\frac{d}{dt} + \lambda \right)^{n-1} e(X) \\ e(X) &= X_{ref} - X \end{aligned} \tag{5}$$

$e(X)$: denotes the error of the controlled greatness;

λ: Positive coefficient;

n: relative degree;

X_{ref}: Reference greatness.

3.1.2 The condition of convergence

The condition of convergence is defined by the equation of Lyapunov.

$$S(x) \cdot \dot{S}(x) \prec 0 \tag{6}$$

3.1.3 Control Calculation

The control algorithm includes two terms, the first for the exact linearization, the second discontinuous one for the system stability.

$$U(t) = U_{eq} + U_n \tag{7}$$

U_{eq}: corresponds to the equivalent order suggested by Utkin (1992). It is calculated starting from the expression:

$$\dot{S}(x) = 0 \tag{8}$$

U_n: is given to guarantee the attractivity of the variable to be controlled towards the commutation surface.

The simplest equation is the form of relay.

$$\begin{cases} U_n = K \cdot satS(x) \\ K \succ 0 \end{cases} \tag{9}$$

3.1.4 Control of id and iq currents

The expression of id is given by the equation:

$$\frac{d}{dt} i_d = \frac{-R_s}{L_d} i_d + \frac{L_q}{L_d} \Omega_r i_q + \frac{1}{L_d} U_d \tag{10}$$

We note that the Eq. (10), show the relative degree of current id with U_d is equal to 1. Therefore the error variable ed is given by:

$$e_d = i_{dref} - i_d$$

The sliding surface of this control is given by:

$$S(i_d) = i_{dref} - i_d$$

The derivative of the equation of S (id) is:

$$\dot{S}(i_d) = \dot{i}_{dref} - \dot{i}_d \tag{11}$$

If we replace the Eq. (10) in (11), the derivative of surface becomes:

$$\dot{S}(i_d) = \dot{i}_{dref} + \frac{R_s}{L_d} i_d - \frac{L_q}{L_d} \Omega_r i_q - \frac{1}{L_d} U_d \tag{12}$$

The low of control is defined by:

$$U_{dref} = U_{deq} + U_{dn} \tag{13}$$

During the sliding mode we have:

$$S(i_d) = 0, \dot{S}(i_d) = 0, i_{dn} = 0$$

We deduce the expression of i_{qeq} from (14):

$$U_{deq} = \left(\dot{i}_{dref} + \frac{R_s}{L_d} i_d - \frac{L_q}{L_d} \Omega_r i_q \right) L_d \tag{14}$$

During the mode of convergence, the derivative of the equation of Lyapunov must be negative.

$$S(X)\dot{S}(X) \leq 0$$

Consequently, the command to the output controller of i_d becomes:

$$U_{dref} = \left(\dot{i}_{dref} + \frac{R_s}{L_d} i_d - \frac{L_q}{L_d} \Omega_r i_q \right) L_d + k_d sat\left(S(i_d)\right) \tag{15}$$

kd: positive gain for id current regulator. In the same way to previous, by developing of the Eq. (16), the control to the output controller of i_q given by (17):

$$\frac{d}{dt} i_q = \frac{-R_s}{L_q} i_q + \frac{L_d}{L_q} \Omega_r i_d - \frac{\Phi_m}{L_q} \Omega_r + \frac{1}{L_q} Uq \tag{16}$$

$$U_{qref} = \left(\dot{i}_{qref} + \frac{R_s}{L_q} i_q - \frac{L_d}{L_q} p\Omega_r i_d + \frac{p\Phi_m \Omega_r}{L_q} \right) + k_q sat\left(S(i_q)\right) \tag{17}$$

k_q: positive gain for i_q current regulator.

4 FUZZY Logic Speed Controller

A proportional-integral controller (PI controller) is a generic control loop feedback mechanism (controller). A PI controller calculates an "error" value as the difference between a measured process variable (speed) and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs (Golea et al., 2002). Two fuzzy logics searched the gains of the PI speed controller, each FL has two inputs and one output Fig. 3. The inputs to the gains of the PI are the normalized error between the reference and actual rotor speed $e(k) = wr^*(k) - wr(k)$, and the normalized change in Flux error $\Delta e(k) = e(k) - e(k-1)$. The centroid defuzzification algorithm is used, in which the output fuzzy variable value is calculated as the centre of gravity of the membership function. In addition, the rule base controlling the defuzzified output according to the fuzzified input values is given in Table 1.

The fuzzy sliding mode controller (FSMC) explained here is a modification of the sliding mode controller equations (9).The surface S(Ω_r) is replaced by two fuzzy shown in Fig. 3.

Table 1 Linguistic rule base for two PI- Fuzzy logic controller.

e \ Δe	NG	NM	NP	ZE	PP	PM	PG
NG	NG	NM	NM	NG	NP	NP	ZE
NM	NM	NM	NM	NM	NP	ZE	PP
NP	NM	NP	NP	NP	ZE	PP	PP
ZE	NP	NP	NP	ZE	PP	PP	PM
PP	NP	NP	ZE	PP	PP	PP	PM
PM	NP	ZE	PP	PM	PM	PM	PG
PG	ZE	PP	PM	PM	PM	PM	PG

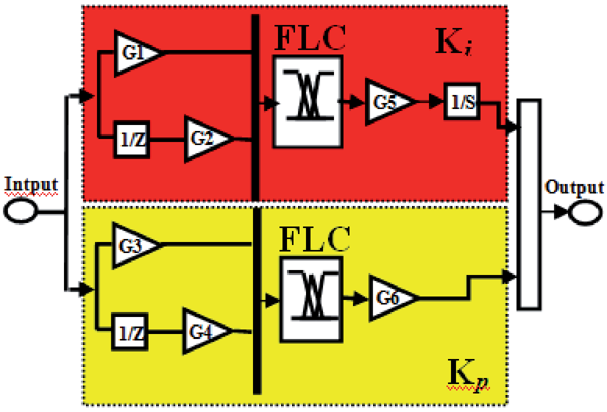

Fig. 3 Simulink model of adaptive FLC for PMSM

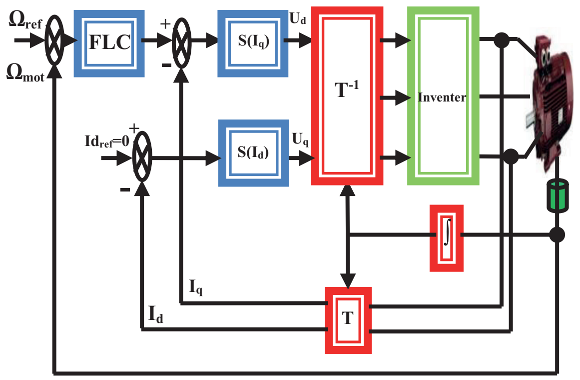

Fig. 4 Schematic global of sliding mode control with FLC controller

5 Results and discussions

To evaluate the peformance of the proposed proposed methods, the model for inter-turn fault has been implemented in the Matlab / Simulink software. The fault of inter-turn winding has been initialized by the control of resistance R_f of the propose model. The healthy machine, R_f is represented by a high value resistor R_f = 200 ohm. On the other hand the PMSM with inter-turn faults, the value of R_f estimated is 0 ohm.

Table 2 summarizes the PMSM parameters used in this simulation (Vaseghi et al., 2011)

Symbol	Description	Magnitude
P	Number of pole pairs	4
Rs	Stator resistance	0.44 Ω
Ls	Stator inductance	2.82 m H
	Winding turn no./slot	40 turns
wr	Synchronos speed	1000 rpm
Vs	Phase voltage	50V
fem	Back EMF (1000 rpm)	34V
Is	Rated current	19A

5.1 Healthy motor

The performance of proposed methods is tested by applying a speed reversal from 100 rd / s to -100 rd / s and with the application of various load torque is shown in Fig. 5. The reversal motoring is applied at a time interval of 0.4 sec. The response of motor speed reaches its reference speed faster and insensitive to load variation using AFLC then FLC.

The Fig. 6 shows the torque of two controllers, we notice that the two controllers are following its reference with high precision.

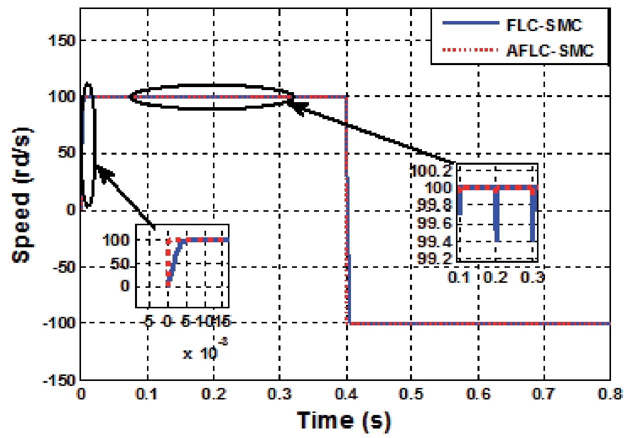

Fig. 5 Evolution of motor's speed for Adaptive FLC-SMC and FLC-SMC.

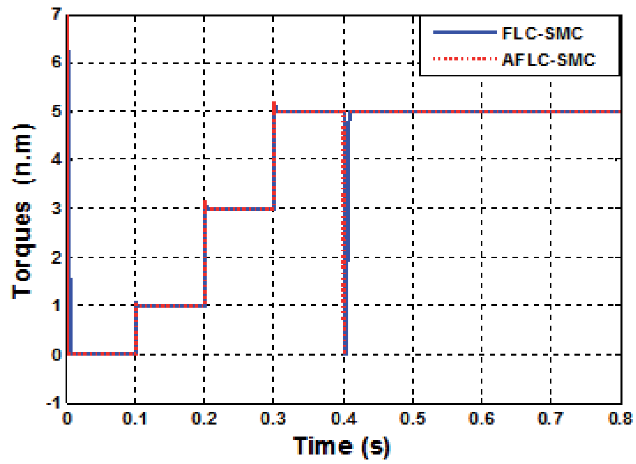

Fig. 6 Evolution of motor's electromagnetic torque for Adaptive FLC-SMC and FLC-SMC.

In order to test the robustness of the proposed controller, we studied the influence of the variations parameters on the performances regulation of speed and torque.

Three cases are considered:

- A variation of ± 50% on inertia, (Fig. 7)
- A variation of ±50% on stator resistances, (Fig. 8),
- A variation of ± 20% on stator inductances. (Fig. 9)

To illustrate the performances of the control, we applied Cr=4N.m load torque at t = 0.4s with level speed reference +100rd/s.

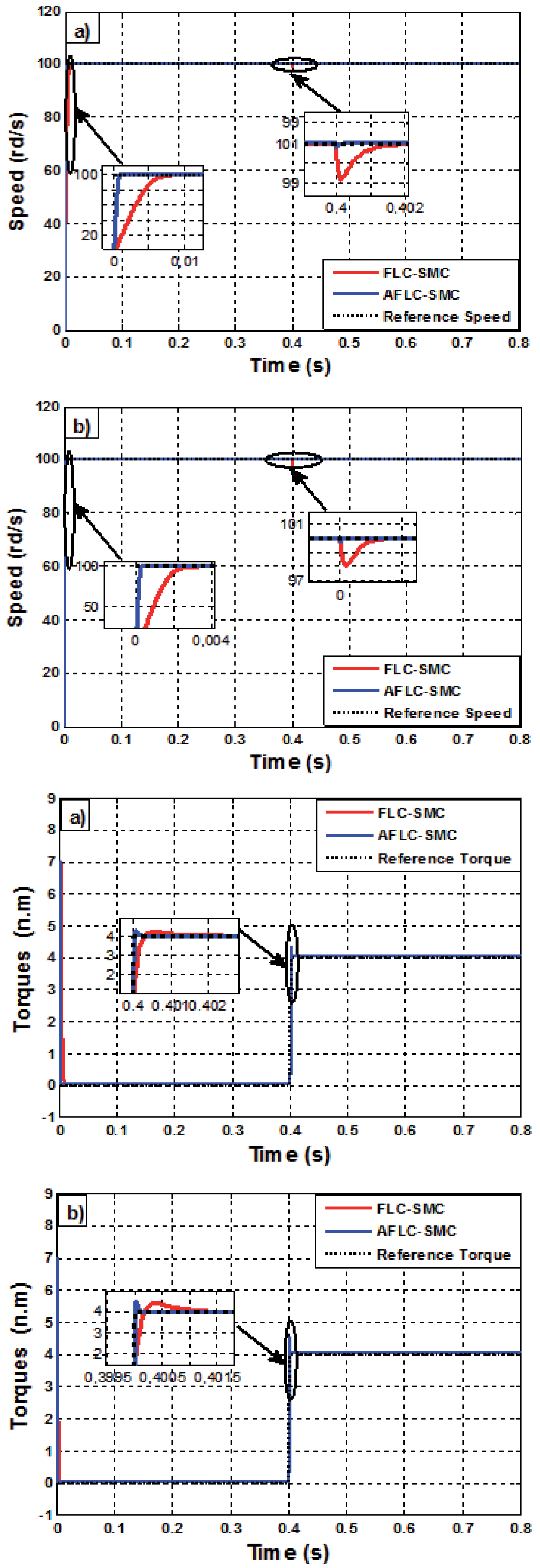

Fig. 7 Robustness test with variation of Inertia: a) J_n +50%J; b) J_n -50%J

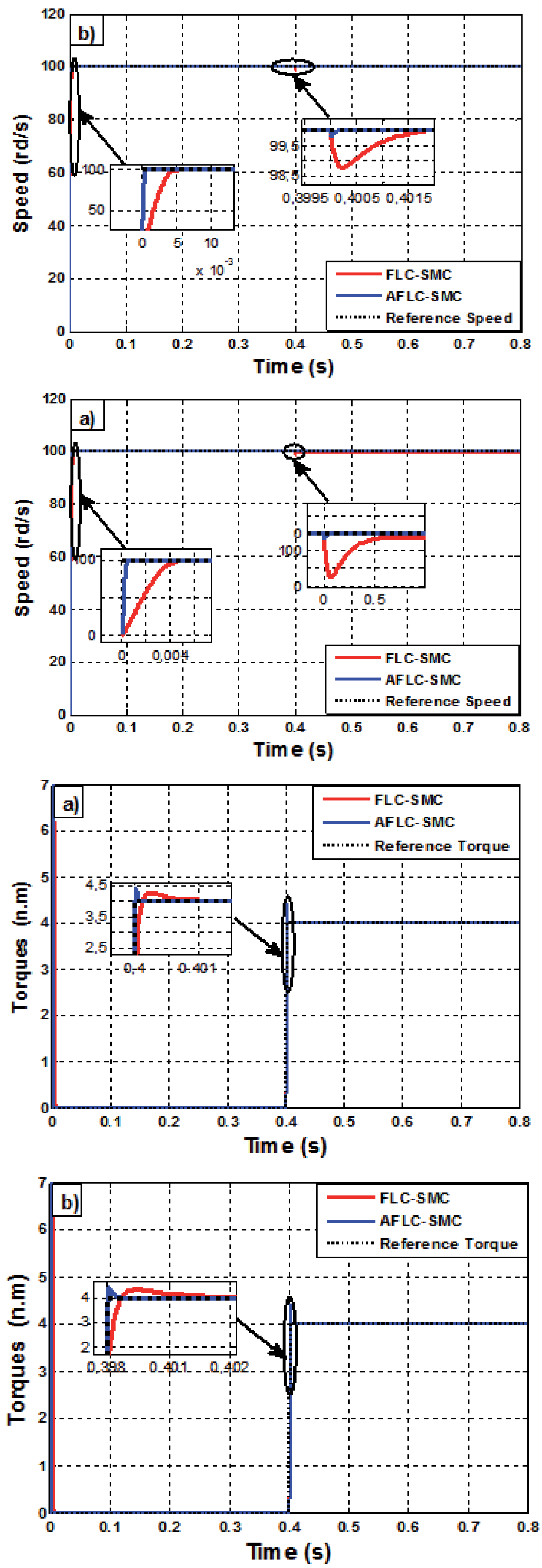

Fig. 8 Robustness test with variation of resistances: a) R_n +50%R_n; b)R_n -50%R_n

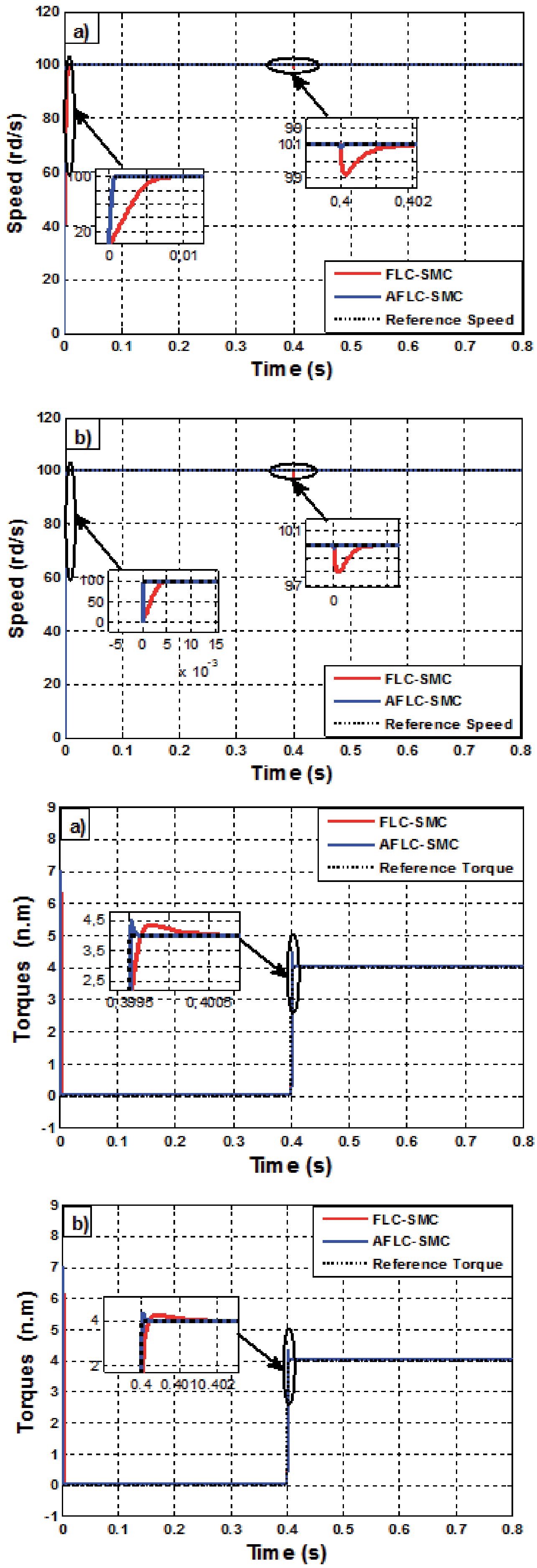

Fig. 9 Robustness test with variation of Inductances: a) $L_n + 50\%L_n$; b) L_n -50%L_n

The simulation results presented in this part shows the robust of two controllers with sliding mode control of a permanent magnet synchronous motor, under stator resistance, moment of inertia and inductance variation. Fig. 8 shows the stator resistance variation applied to examine our controller (AFLC-SMC). In this case, the value of stator resistance was changed with ±1.5Rn. Where, Fig. 7 present the moment of inertia variation with ±1.5Jn, and the inductance variation ±1.2Ln, presented in Fig. 9.

It's seen in Fig. 7, 8 and 9 that the proposed speed controller (AFLC-SMC) allows to achieve a faster response and reject the harmonic ripples (motor parameters variations). Also, a faster motor torque response has been achieved with proposed technique compared to (FLC-SMC); as shown in Fig. 7, 8 and 9.

In conclusion simulations results are presented in Fig. 7, 8 and 9 show that the proposed controller (AFLC-SMC) is adaptive and robust to the effects of the variation of motor parameters such as stator resistance, stator inductance and moment of inert.

5.2. Faulty motor

In this part, we tested the robustness of the proposed method with different numbers of inter-turn short circuit while maintaining fixed fault resistance at 0.1 ohm (Figs. 10, 11 and 12).

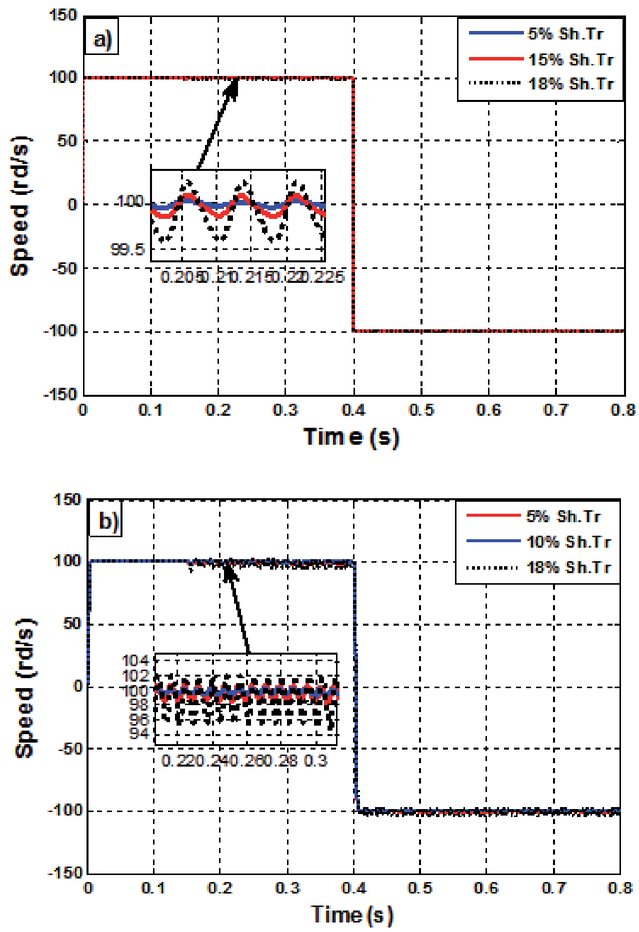

Fig. 10 The speed motor with inter-turn short circuit fault at t=0.15 for: a) AFLC-SMC, b) FLC-SMC.

The Fig. 10 shows the speed profile for the two controllers; we find that the speed remains almost constant and insensitive to variations in the number of short circuit turns. This proves that AFLC controller performances are more robust compared to FLC regulator.

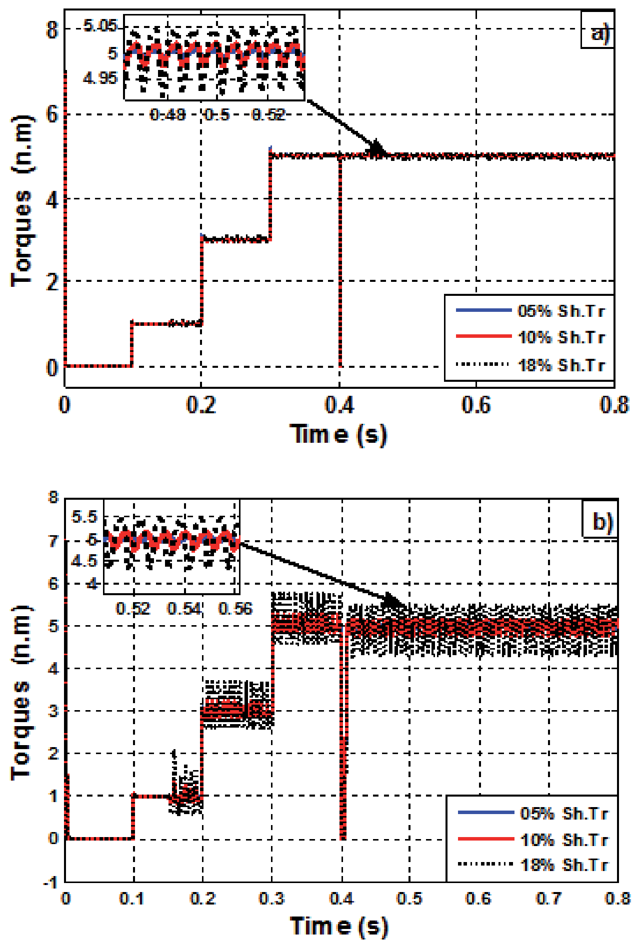

Fig. 11 The electromagnetic torque with inter-turn short circuit fault at t=0.15 for: a) AFLC-SMC, b) FLC- SMC

Regarding the Fig. 11 and 12 of torque and stator flux, it is noteworthy that when using the AFLC regulator, the ripple is reduced compared to that obtained with the FLC. The Adaptive FLC regulator helps reducing the undulations that cause the rapid deterioration of the stator windings. Therefore, it promotes the growth of the stator winding lifetime.

Figures 13 and 14 show the THD of the stator current of the motor phase (a) to the healthy and degraded state and when this latter is subjected to different loads and speed of rotation variation. The AFLC-SMC control helps to reduce harmonic rate at which the stator winding is submitted and consequently the decrease in the motor overheating because the current may increase its nominal value and will cause rapid deterioration of stator winding.

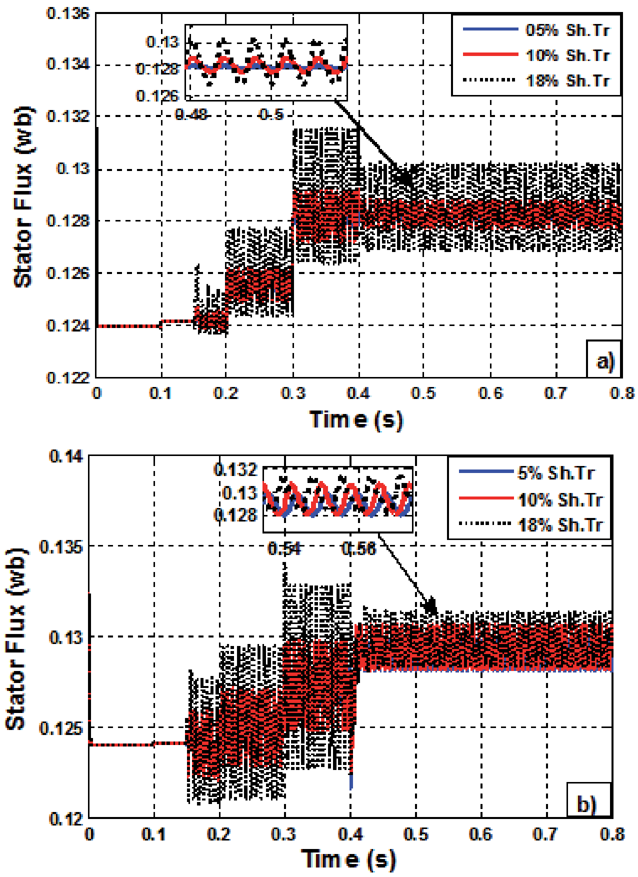

Fig. 12 The stator flux with inter-turn short circuit fault at t=0.15 for: a) AFLC-SMC, b) FLC-SMC.

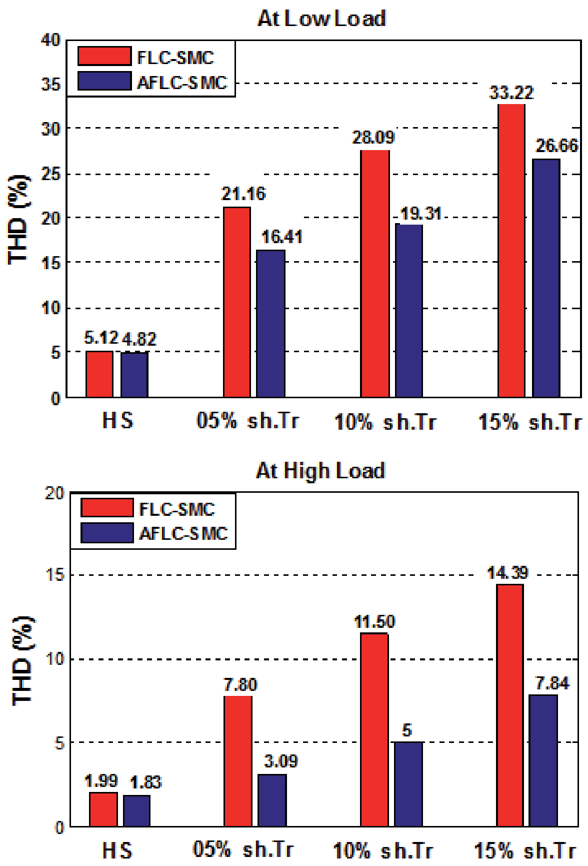

Fig. 13 The THD for healthy and Faulty motor at V=104.8rd/s.

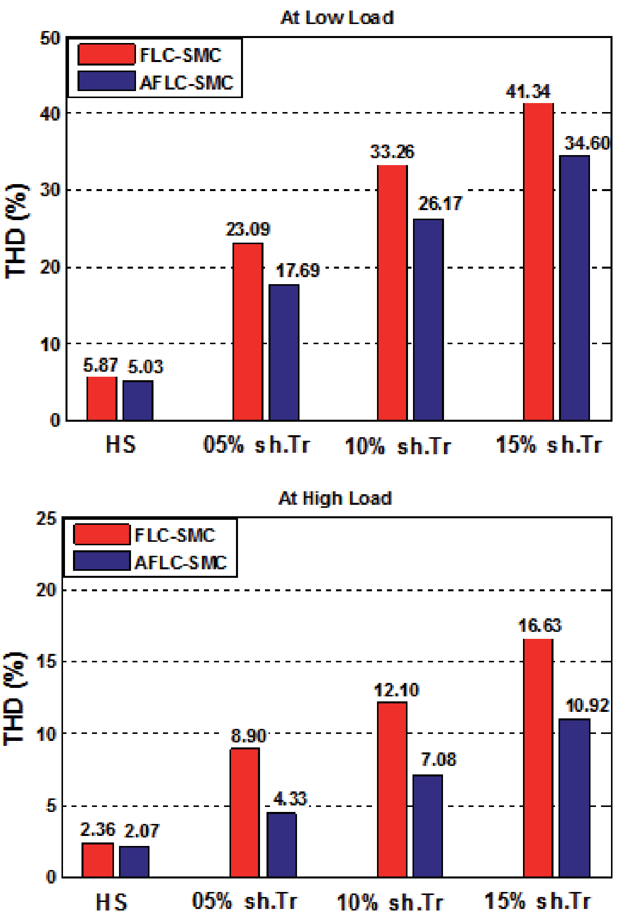

Fig. 14 The THD for healthy and Faulty motor at V=160 rd/s.

6 Conclusion

The paper presents a new approach for speed control of PMSM using hybrid AFLC-SMC by taking account of the presence of inter-turn short circuit fault. A comparative study between the conventional fuzzy and the adaptive fuzzy logic controller are presented in order to select the best regulator for control and diagnosis faults. The overall system (AFLC-SMC) performance has been investigated at different dynamic operating conditions. It is concluded that the proposed controller shown superior performances and robust stability despite the presence of external load disturbances and stator faults compared to FLC-SMC.

References

Ahmed, M. S. S., Ping, Z., Jie, W. Y. (2007) Modified Sliding Mode Controller with Extended Kalman Filter for Stochastic Systems. In: 2007 IEEE International Conference on Control and Automation, Guangzhou, May 30 2007-June 1 2007, pp. 630-635. DOI: 10.1109/ICCA.2007.4376432

Ameur, A., Mokhtari, B., Essounbouli, N., Nollet, F. (2013) Modified Direct Torque Control for Permanent Magnet Synchronous Motor Drive Based on Fuzzy Logic Torque Ripple Reduction and Stator Resistance Estimator. *Journal of Control Engineering and Applied Informatics*. 15(3), pp. 45-52.

Ameur, A., Mokhtari, B., Mokrani, L., Azoui, B., Essounbouli, N., Hamzaoui, A. (2010) An Improved Sliding Mode Observer for Speed Sensorless Direct Torque Control of PMSM Drive with a Three-Level NPC Inverter Based Speed and Stator Resistance estimator. *Journal of Electrical Engineering*. 10(4), pp. 1-10. URL: http://www.jee.ro/covers/art.php?issue=WI1256703931W4ae7c7bb6475c

Ameur, A., Ameur, K., Mokhtari, B. (2013) MRAS for Speed Sensorless Direct Torque Control of a PMSM Drive Based on PI Fuzzy Logic and Stator Resistance Estimator. *Transaction on Control and Mechanical Systems*. 2(7), pp. 321-326. URL: http://www.tsest.org/index.php/TCMS/article/view/140

Bessa, W. M., Barrêto, R. S. S. (2010) Adaptive fuzzy sliding mode control of uncertain nonlinear systems. *Sba: Controle & Automação Sociedade Brasileira de Automatica*. 21(2), pp. 117-126. DOI: 10.1590/S0103-17592010000200002

Cheng, N. B., Guan, L. W., Wang, L. P., Han, J. (2011) Chattering reduction of sliding mode control by adopting nonlinear saturation function. *Advanced Materials Research*. 143-144, pp. 53-61. DOI: 10.4028/www.scientific.net/AMR.143-144.53

Choi, J. H., Gu, B.-G., Won, Ch.-Y. (2013) Modeling and Analysis of PMSMs under Inter Turn Short Faults. *Journal of Electrical Engineering and Technology*. 8(5), pp. 1243-1250. DOI: 10.5370/JEET.2013.8.5.1243

Farooq, J. A., Raminosoa, T., Djerdir, A., Miraoui, A. (2008) Modelling and simulation of stator winding inter-turn faults in permanent magnet synchronous motors. *COMPEL - The international journal for computation and mathematics in electrical and electronic engineering*. 27(4), pp. 887-896. DOI: 10.1108/03321640810878306

Golea, N., Golea, A., Benmahammed, K. (2002) Fuzzy model reference adaptive control. IEEE Transactions on Fuzzy Systems. 10(4), pp. 436-444. DOI: 10.1109/TFUZZ.2002.800694

Masumpoor, S, Yaghobi, H., Khanesar, M. A. (2015) Adaptive sliding-mode type-2 neuro-fuzzy control of an induction motor. Journal of Expert Systems with Applications. 42(19), pp. 6635-6647. DOI: 10.1016/j.eswa.2015.04.046

Slotine, J.-J., Li, W. (1998) *Applied nonlinear control*. Prentice Hall, USA.

Tallam, R. M., Habetler, T. G., Harley, R. G. (2000) Transient model for induction machines with stator winding turn faults. In: *Industry Applications Conference, 2000*. Conference Record of the 2000 IEEE, Vol. 1, Rome, Oct. 8-12, 2000, pp. 304-309. DOI: 10.1109/IAS.2000.881128

Tseng, M.-L., Chen, M.-S. (2010) Chattering reduction of sliding mode control by low-pass filtering the control signal. *Asian Journal of Control*. 12(3), pp. 392-398. DOI: 10.1002/asjc.195

Utkin, V. I. (1992) *Sliding mode in control and optimization*. Springer, Berlin. DOI: 10.1007/978-3-642-84379-2

Vaseghi, B., Takorabet, N., Nahid-Mobarakeh, B. Meibody-Tabar, F. (2011) Modelling and study of PM machines with inter-turn fault dynamic model–FM model. *Electric Power Systems Research*. 81(8), pp. 1715-1722. DOI: 10.1016/j.epsr.2011.03.017

Wang L.-X. (1993) Stable adaptive fuzzy control of nonlinear systems. *IEEE Transactions on Fuzzy Systems*. 1(2), pp. 146-155. DOI: 10.1109/91.227383