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Diagnosis of Turn Short Circuit Fault in PMSM Sliding-mode Control based on Adaptive Fuzzy Logic-2 Speed Controller.

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Abstract

The diagnosis of faults in industrial systems is essential to minimize the production losses, increase the safety of the operator and the equipment. In this paper, a fault diagnosis method is presented for the diagnosis of inter-turn short circuit fault in PMSM (Permanent magnet synchronous machine) based on the comparative analysis of three types of controllers. We were interested in the sliding mode control (SMC) of the PMSM using Type1 Fuzzy logic controller (T1FLC), Type 2 Fuzzy logic controller (T2FLC) and Type2 adaptive Fuzzy logic controller (T2AFLC) by taking account of the presence of inter-turn short circuit fault. This study aims to select the most robust controller against the stator faults, load torque variation and reversing rotation speed. Simulation tests were performed respectively for these controllers depending on the evolution of the load, speed and severity degrees of failures. Tests regarding these three controllers associated with the sliding mode control were carried out on a PMSM 5KW exposed to different loads for a functioning in healthy and degraded state. The obtained simulation results confirm the superiority and robustness of T2AFLC-SMC (insensitive to the load torque and the rotation direction, faster response time, decrease in the speed oscillations, electromagnetic torque and stator flux) compared to T1FLC-SMC and T2SMC-FLC.

Key words:
Diagnosis, inter-turn fault**,** PMSM, sliding mode control, type-1 fuzzy logic controller, type-2 fuzzy logic controller.

1. Introduction

High dynamic performance of servo motor drives is indispensable in many applications of today’s automatically controlled machines. AC motor control has attracted much attention recently in the power electronics field [1]. Due to its increased performance, the synchronous permanent magnet motor is currently the motor reference in an industrial world when the requirements are always higher from point of view the economical and the technical due to some advantages like: more simplicity, low maintenance, low dependency on the motor parameters, good dynamic torque response, high rate torque/inertia and simplicity of design [2]. One of the most common faults in the electrical motors is the inter-turn short circuit fault in one of the stator coils [3]. A turn fault in the stator winding of the electrical machine causes a large circulating current in the shorted turns. If the turn fault left undetected, the turn faults propagate and leads to phase–ground or phase–phase faults [4],[5]. The inter-turn fault is mostly caused by mechanical stress, moisture and partial discharge, which is accelerated for electrical machines supplied by inverters [6]. There is a lot of control applied for PMSM, like speed and torque (FOC, DTC) which results in high performance system response and simplifies the Classical PI speed control of PMSM. However, this strategy design of such systems plays a crucial role on these performances. A fixed PI gain controller does not provide satisfactory control performance in the presence of parameter variations and disturbances under a wide range of driving conditions [7].

Many researchers have proposed a lots of control strategies to tune the gain values of PI, like Ziegler-Nichols [8]. In this method, a system model and the control parameters are required to determine the parameters of the PI controller from the plant step response. However, the step response yields a high overshoot. In addition, the control signal required for the adequate performance of the system is too high.

Therefore based speed controller is in demand to get high performance drive. To overcome the above mentioned drawbacks and improve the system performance, adaptive control based speed controllers are required, such as self tuning PISC, SMC, artificial intelligent based controllers like FLSC, neural networks, neuro-fuzzy, genetic algorithms (GAs are introduced to address difficulties in selecting correction and on-line tuning of the PI gains). [7]-[18].

Sliding-mode control (SMC) has been widely applied to robust control of nonlinear systems. SMC offer good stability, robustness, and consistent performance under the presence of uncertainties and external disturbances [17], [18]. However, since a discontinuous control action is involved, chattering will take place [10]-[12]. In addition, for conducting an effective switching scheme and guaranteeing the stability of an SMC system, a good estimation of the uncertainty bound including the unknown dynamics, parameter variations and external load disturbance, must be available at the outset of the design [14]. Such bounds cannot be estimated easily, some control strategies need to be applied, with the disadvantage of large control efforts needed to preserve the stability of the closed-loop system.

Due to the possibility to express human experience in an algorithmic manner, fuzzy logic has been largely employed in the last decades to both control and identification of dynamical systems

[9]. In spite of the simplicity of this heuristic approach, in some situations a more rigorous mathematical treatment of the problem is required. Recently, much effort has been made to combine fuzzy logic with nonlinear control methodology and a proportional plus integral controller [19]. In [17] a globally stable adaptive fuzzy controller was proposed using Lyapunov stability theory to develop the adaptive law. Combining fuzzy logic with sliding mode control, in [18] used the switching variable to define a fuzzy boundary layer. Some improvements to this control scheme appeared in [20]-[22].

Many researchers have shown that type-1 FLS have difficulties in modeling and minimizing the effect of uncertainties. In recent years, the conventional fuzzy logic called Type-1 has been generalized to a new type of fuzzy logic Type-2 [23]. Mendel and his team have contributed to its development, they built their theoretical foundation, and demonstrated its effectiveness and superiority in practice and theoretical compared to the fuzzy-type 1[24], [25]. T2FLSs are more complex than type-1, the major difference being the present of type-2 is their antecedent and consequent sets. T2FLSs gives better performance results than the type 1 Fuzzy Logic Systems (T1FLSs) on application of the function approximation, modeling and control. Several publications have demonstrated the interest in the use of fuzzy-type-2 systems, alone or combined with other robust methods and have shown that it provide good solutions, especially in the presence of uncertainties [26]. In [15] used Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO) to optimize the membership functions parameters of a fuzzy logic controller in order to find the optimal intelligent controller for an autonomous wheeled mobile robot. An adaptive hybrid interval type-2 fuzzy neural network (FNN) controller incorporating sliding mode and Lyapunov synthesis approaches has proposed by[16] to handle the training data corrupted by noise or rule uncertainties for a class of uncertain nonlinear multivariable dynamic systems.

The diagnosis of the control of PMSM became very important in industrial environment especially for the electric drives [27]. Several researchers were interested in electric motors diagnosing faults in closed loop in order to observe the effect of conventional and intelligent regulators controllers in the presence of electrical machine faults [27] -[30]. For example, in [28], a sliding mode control accompanied by a comparison between two controllers: fuzzy logic sliding mode controller and sliding mode controller in the presence of faults in rotor (broken bar) was presented. A comparison between PI controller and fuzzy controller associated with the vector control of IMs in the presence of defective bar was carried out in [29].

In this paper, a comparative study of three types of controllers T1FLC, T2FLC and T2AFLC associated with the SMC control dedicated to fault diagnosis of an inter-turn short circuit. This comparison reveals which of the three controllers is the most robust for the motor control and faults diagnosis. Tests regarding these three controller 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.

2. Faulty PMSM model for inter-turn short-circuit detection

The faulty PMSM model used for inter-turn short-circuit detection is based on a former study with less modeling assumptions (voltage drops due to short-circuit reduction is taken into account) to make the PMSM model more sensitive to windings faults. The model enables the fault localization with the use of angle θ_{cc} (equal to 0, 2π/3 or 4π/3 for a short-circuit respectively on phase A, phase B or phase C) and the number of short-circuit turns ns/c (ratio between short-circuited turns and the whole turns on a stator winding). Figure 1 shows the basic model for fault diagnosis with inter-turn short-circuit on phase C (θ_{cc} = 4π/3).

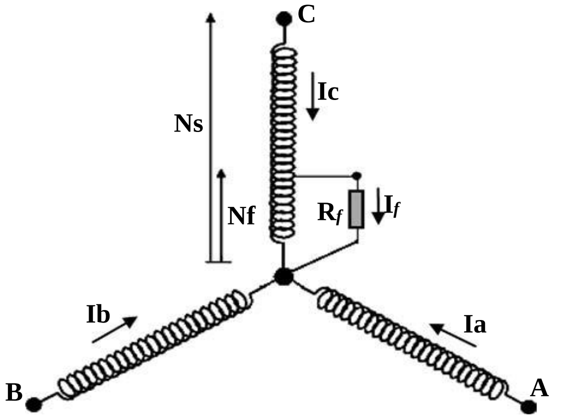


Fig. 1.Three phase stator winding with turn fault in Phase “c”

Setting up the mesh equations for the circuit in Fig. 1 will express the voltage equations as:

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

Where [Vs], [Is] and [Es] 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:

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

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

The voltage equation of the faulty loop (c_{s2}) is:

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

$$[T_{s/c}]=\frac{1}{3}\begin{bmatrix} 1+2\cos(\theta_{cc}) \\ 1+2\cos\left(\theta_{cc}-\frac{2\pi}{3}\right) \\ 1+2\cos\left(\theta_{cc}-\frac{4\pi}{3}\right)\end{bmatrix} \text{Short–circuit matrix}$$

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

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

$$T_e=\frac{[E_s]\,[I_s]-e_{a2}i_f}{\Omega}$$

$$T_e-T_l=J\,\frac{d\Omega_r}{dt}. \quad (3)$$

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

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 [28].

3.1.1 Choice of the switching surface:

J. Slotine proposes a form of general equation to determine the sliding surface [31].

$$S(X)=\left(\frac{d}{dt}+\lambda\right)^{n-1}e(X)$$
$$e(X)=X_{ref}-X \quad (4)$$

$e(X)$: 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 .

$$S(x).\dot{S}(x) \prec 0 \quad (5)$$

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.

$$U(t)=U_{eq}+U_n \quad (6)$$

U_{eq} : corresponds to the equivalent order suggested by Utkin [32]. It is calculated starting from the expression: $\dot{S}(x)=0$ (7)

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.

$$\begin{cases} U_n = K.satS(x) \\ K \succ 0 \end{cases} \quad (8)$$

3.2 Strategy of regulation of PMSM on three surfaces:

The figure (2) presents the diagram of the regulation by sliding mode using the principle of the method of regulation in cascade, the structure contains a control loop of speed which generates the reference I_q which imposes the U_q. The control of U_d is imposed by the control of I_d current.

3.2.1 Control of speed:

The surface selected for the control of speed error is:

$$S(\Omega_r)=\Omega_{ref}-\Omega_r \quad (9)$$

The derivative of the equation (10) is: $\dot{S}(\Omega_r) = \dot{\Omega}_{ref} - \dot{\Omega}_r$ (10)

The law of control is defined by:

$$I_{qref} = I_{qeq} - I_{qn} \tag{11}$$

$$\dot{S}(\Omega_r) = \dot{\Omega}_{rref} - \frac{3p}{2}\frac{(L_d - L_q)i_d + \Phi_f}{J} i_q + \frac{C_r}{J} + \frac{f_r}{J}\Omega_r \tag{12}$$

If we replace the equation (11) in (12) we obtain:

$$\dot{S}(\Omega_r) = \dot{\Omega}_{rref} - \frac{3p}{2}\frac{(L_d - L_q)i_d + \Phi_m}{J}(i_{qeq} + {}_{qn}) + \frac{C_r}{J} + \frac{f_r}{J}\Omega_r \tag{13}$$

During the sliding mode we have:

$$S(\Omega_r) = 0, \dot{S}(\Omega_r) = 0, i_n = 0 \tag{14}$$

We deduce the expression of i_{qeq} from (15):

$$i_{qeq} = \frac{\dot{\Omega}_{rref} + \frac{f_r}{J}\Omega_r + \frac{C_r}{J}}{\frac{3p}{2}\left[\frac{(L_d - L_q)i_d + \Phi_m}{J}\right]} \tag{15}$$

We replace equation (15) in (14) one obtains:

$$\dot{S}(\Omega_r) = \frac{3p}{2}\left[\frac{(L_d - L_q)i_d + \Phi_m}{J}\right] i_{qn} \tag{16}$$

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

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

According to the equation (8), the discontinuous function i_{qn} defined by:

$$i_{qn} = k_{\Omega_r} sat(S(\Omega_r)) \tag{17}$$

$K_{\Omega r}$: Positive gain for speed regulator.

The control to the output controller of i_{qref} given by:

$$i_{qref} = \frac{\dot{\Omega}_{rref} + \frac{f_r}{J}\Omega_r + \frac{C_r}{J}}{\frac{3p}{2}\left[\frac{(L_d - L_q)i_d + \Phi_m}{J}\right]} + k_{\Omega_r} sat(S(\Omega_r)) \tag{18}$$

3.2.2 Control of i_d and i_q currents:

The expression of id is given by the equation:

$$\frac{d}{dt} i_d = \frac{-R_s}{L_d} i_d + \frac{L_q}{L_d}\Omega_r i_q + \frac{1}{L_d} U_d \tag{19}$$

We note that the equation (19), 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: $\dot{S}(i_d) = \dot{i}_{dref} - \dot{i}_d$ (20)

If we replace the equation (19) in (20), the derivative of surface becomes:

$$\dot{S}(i_d) = \dot{i}_{dref} + \frac{R_s}{L_d} i_d - \frac{L_q}{L_d} \Omega_r i_q - \frac{1}{L_d} U_d \tag{21}$$

The low of control is defined by:

$$U_{dref} = U_{deq} + U_{dn} \tag{22}$$

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 (23):

$$U_{deq} = \left(\dot{i}_{dref} + \frac{R_s}{L_d} i_d - \frac{L_q}{L_d} \Omega_r i_q \right) L_d \tag{23}$$

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:

$$U_{dref} = \left(\dot{i}_{dref} + \frac{R_s}{L_d} i_d - \frac{L_q}{L_d} \Omega_r i_q \right) L_d + k_d sat(S(i_d)) \tag{24}$$

kd: positive gain for id current regulator. In the same way to previous, by developing of the equation (25), the control to the output controller of i_q given by (26):

$$\frac{d}{dt} i_q = \frac{-R_s}{L_q} i_q + \frac{L_d}{L_q} \Omega_r i_d - \frac{\Phi_m}{L_q} \Omega_r + \frac{1}{L_q} Uq \tag{25}$$

$$U_{qref} = \left(\dot{i}_{qref} + \frac{R_s}{L_q} i_q - \frac{L_d}{L_q} p\Omega_r i_d + \frac{p\Phi_m \Omega_r}{L_q} \right) + k_q sat(S(i_q)) \tag{26}$$

k_q: positive gain for i_q current regulator.

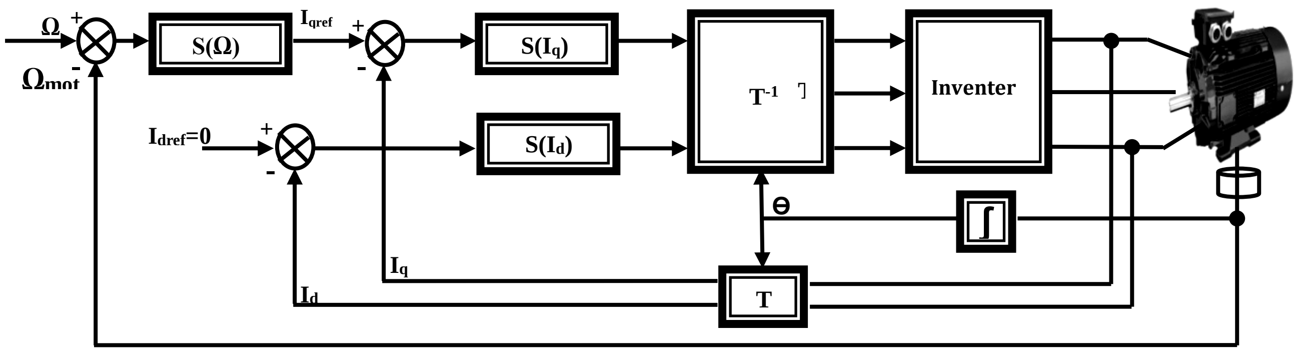


Fig.2: Schematic global of sliding mode control with strategy of three surfaces

4. Fuzzy logic control

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 [33].Two fuzzy logics searched the gains of the PI speed controller, each FL has two inputs and one output figure (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 $\Delta e(k) = e(k) - e(k-1)$ [34]. 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 (8).

↓ de	→ e	NB	NM	NS	ZE	PS	PM	PB
	N	P	NS	ZE	PS	PM	PB	PB
	ZE	PB	P	NS	ZE	PS	PM	PB
	P	PB	PB	PS	NS	ZE	PS	PM

Table 1. Linguistic rule base for two fuzzy logic controllers.

The three surfaces ($S(\Omega_r)$, $S(I_d)$, $S(I_q)$) are replaced by two fuzzy shown in figure 3.

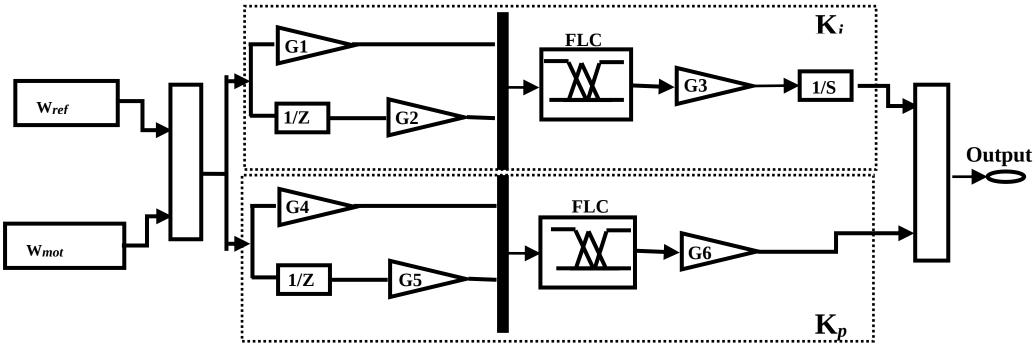


Fig.3. Simulink model of adaptive FLC for PMSM

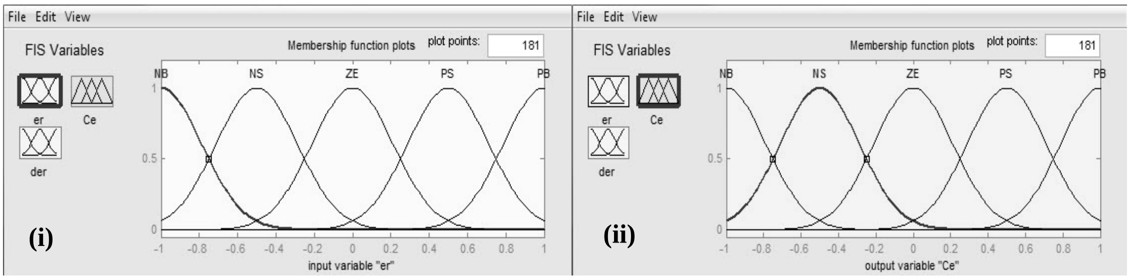


Fig. 4 The Type-1 fuzzy membership functions are: (i) error speed $e\omega_r$ and change in error speed $\Delta e\omega_r$ and (ii) output variable T_e^*

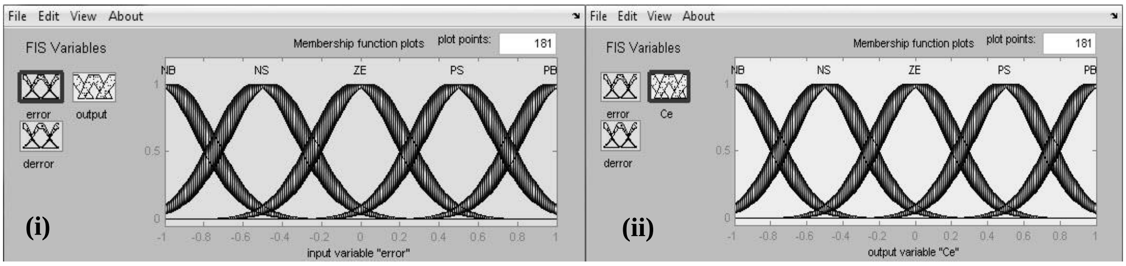


Fig. 5 The Type-2 fuzzy membership functions are: (i) error speed $e\omega_r$ and change in error speed $\Delta e\omega_r$ and (ii) output variable T_e^*

5. Results and discussions

The proposed 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. The parameters of PMSM [35]: P=5Kw; Rs=0.44 ohm; Ls=2.82 m H; f=66.67Hz.

1. Healthy motor

The performance of PMSM is tested by applying a speed reversal from 104.8 rd /s to -104.8rd / s and with the application of various load torque is shown in Fig. 6. The reversal motoring is applied at a time interval of 0.5 sec. The response of motor speed reaches its reference speed faster using T2AFLC then T1FLC and T2FLC.

The figures (7 and 8) are respectively: stator flux and the torque, we notice that the three controllers are following its reference with high precision.

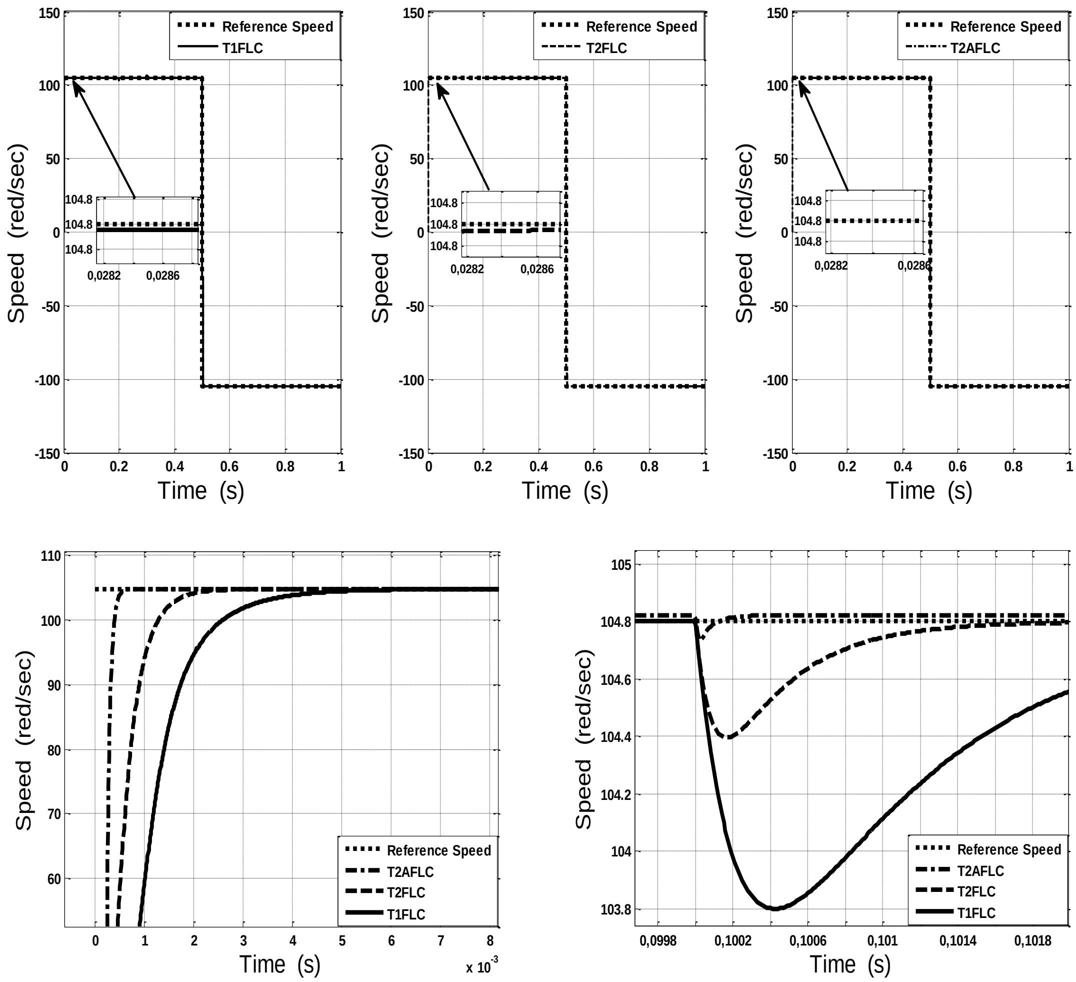
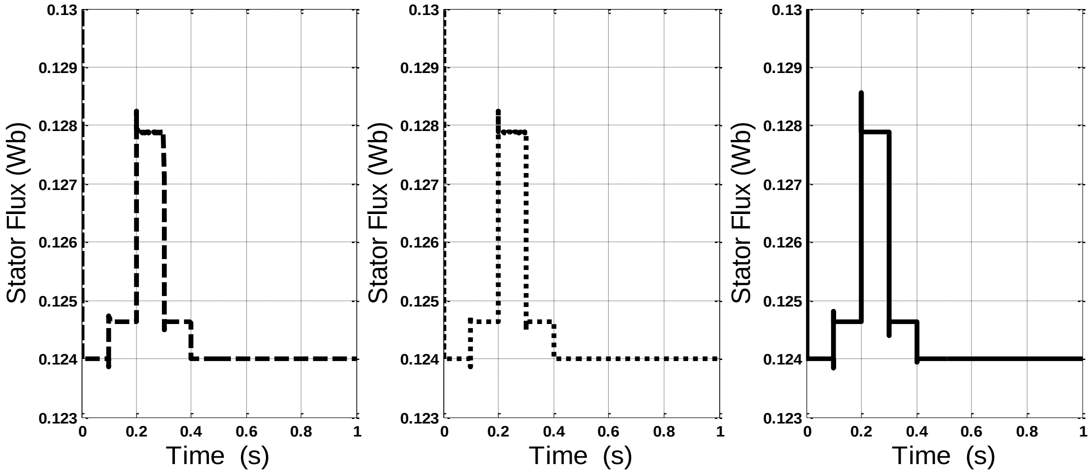


Fig.6. The rotor speed motor and it's Zoom



a) T1FLC b) T2FLC c) T2AFLC

ig.7.Ev tor flux

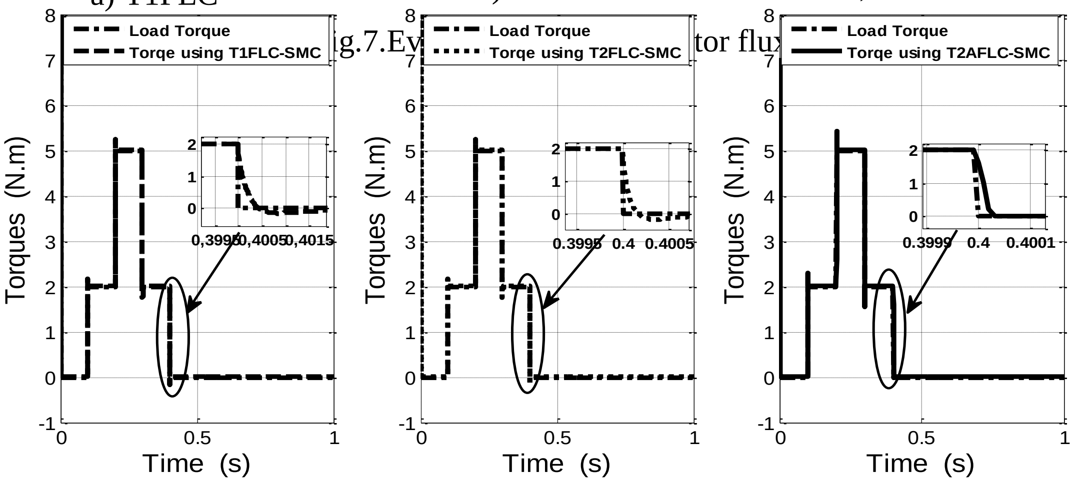
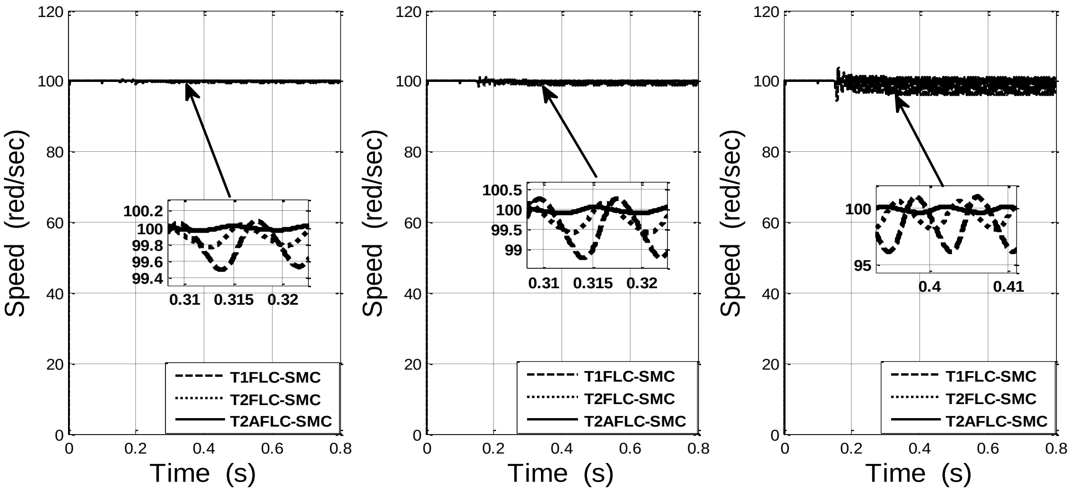


Fig.8. Evolution of electromagnetic torque

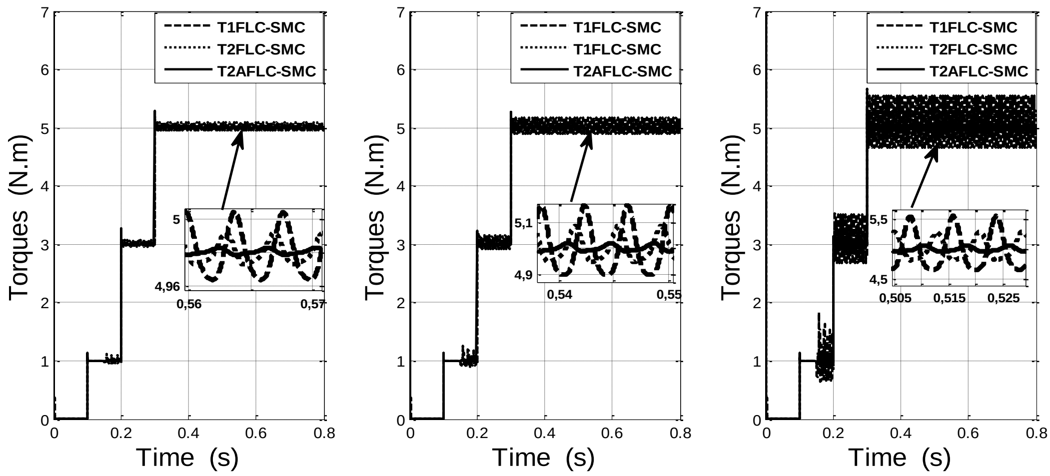
2. Faulty motor

Figures (9, 10 and 11) show: the speed profile, the electromagnetic torque and the stator flux respectively. It is noteworthy that through using T2AFLC controller, the ripple ratio is less compared to that obtained with the T1FLC and T2FLC.The T2AFLC controller helps reduce the ripples responsible for the rapid degradation of the stator windings. Consequently, it increases the lifetime of the winding and facilitates the predictive diagnosis of the damage of the stator winding turns.



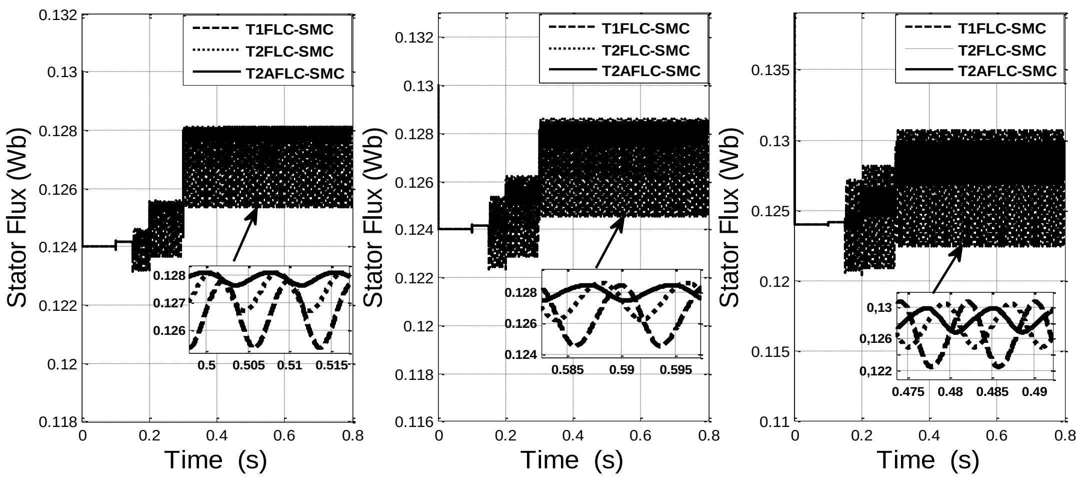
a) 05 shorted turns | b) 10 shorted turns | c) 20 shorted turns

Fig.9.The speed motor with inter-turn short circuit fault at t=0.15 for r_f=0 ohm.



a) 05 shorted turns | b) 10 shorted turns | c) 20 shorted turns

Fig.10. The electromagnetic torque with inter-turn short circuit fault at t=0.15 for r_f=0 ohm.



b) 05 shorted turns | a) 10 shorted turns | c) 20 shorted turns

Fig.11. The stator flux motor with inter-turn short circuit fault at t=0.15 for r_f=0 ohm.

6. Conclusion and future scope

In this work, T1FLC, T2FL and T2AFLC based SMC of PMSM dedicated to the stator faults are presented in order to select the best regulator for control and diagnosis faults. The T1FLC offers poor dynamic response and robust control under the conditions of reversing rotation speed, stator faults and load torque disturbances. In order to improve the performance, T2FLC is incorporated in place of T1FLC. Moreover, with the same number of membership and the same gain maximum control, a new T2AFLC replaces T2FLC. The T2AFLC offers an excellent dynamic as well as steady state response of torque, stator flux and motor speed with less ripple contents and also robust control to fault stator compared to T1FLC and T2FLC.

This work can serve as a support for an improved command and a tool for other electrical and / or mechanical faults with another control using intelligent controllers optimized by the genetics algorithm or particle swarm optimization.

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