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Impact of Artificial Intelligence for Performance Improvement of Direct Torque Control of Induction Motor based on Second Order Sliding Mode Controller

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Abstract

This work deals with the performance improvement study of the direct torque control of induction Motor based on genetic fuzzy Second Order Sliding Mode Control. The main objective is to improve the performance of the system by reducing electromagnetic torque ripples because the direct torque control using conventional Second Order Sliding Mode Control regulators has certain disadvantages such as significant flux, torque ripples and sensitivity to parametric variations. To overcome these drawbacks, we apply a new type with more robust regulators such as the genetic fuzzy second order sliding mode control. To provide a numerical comparison between different controllers, a performance index based on speed error is assigned.

The simulation results for various scenarios show the high performances of the proposed direct torque control genetic fuzzy Second Order Sliding Mode Control system by effectively accelerating system response, reducing torque and flux ripple and a very satisfactory performance has been achieved.

Keywords: *induction machine, direct torque control, fuzzy Second Order Sliding Mode Control, genetic algorithm*

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I. INTRODUCTION

The control of IM is considered complicated because of the difficulty of obtaining the decoupling of the torque and the flux. In order to overcome these difficulties, high-performance algorithms have been developed [2], [3], and [6]. Among the control, techniques currently applied to asynchronous machines to ensure the pursuit of predetermined trajectories, robustness to parameter variations and disturbance rejection with an unknown response we can find direct torque control and sliding mode control.

Due to the advances in power electronics and the recent revolutions of computers Sliding Mode Control have made an important research field, which can be developed by a lot of scientists in many countries. The synthesized control consist of two main terms, the first allows the approach to this surface and the second maintaining sliding along it towards the origin of the phase plane [1] [10] [11]. The global controlled as well constructed ensures good tracking performance, rapid dynamic and short response time.

Nevertheless, the classic sliding mode of the first order has a phenomenon of chattering, which is a significant disadvantage. To reduce this phenomenon a new class of SMC algorithm, called the second-order SMC (SOSMC)

Algorithm, has been proposed, this approach allows reducing the chattering effect. In order to develop a robust DTC, current researchers have proposed the fuzzy logic technique that is part of artificial intelligence to solving robustness problems.

In last years, the fuzzy logic controller has improved successfully as result of nonlinear and complex processes [16] [22]. The general configuration uses type IF-THEN type with linguistic rules. The main advantage of this approach is that it does not need a precise mathematical model of the electric machine, FLCs is robust and its performance is insensitive to parameter variations [8], [9], [12], [17], [23].

In our case, we have proposed a DTC with a speed controller based on the fuzzy second order sliding mode control to obtain a more flexible control. This last solution allowed the reduction or even the attenuation of the chattering phenomenon while keeping the properties of robustness [13] [14].

A hybrid approach integrating the genetic algorithms (GA) with the fuzzy logic second order sliding mod controller based direct torque control of induction motor to enhance the system performance and stability[14],[15],[24].The developed algorithm achieves an optimized tuning of a fuzzy SOSMC scaling factor

The strategy proposed in this work is the study of the dynamic behavior of induction motor controlled by a DTC during a speed adjustment by regulators (SOSMC) and by regulators based on genetic fuzzy second order sliding mode. Simulation results reveal that the FSOSMC-DTC has a very robust behavior against the SOSMC-DTC.

II. MODELING OF THE INDUCTION MOTOR

By applying the Park transformation to the model of the induction motor, the equations are expressed in a reference frame linked to the rotating field as follows [1]:

$$\begin{aligned} V_{ds} &= R_{ds} i_{ds} + \frac{\mathrm{d}\varphi_{ds}}{\mathrm{d}t} - \omega_s \varphi_{qs} \\ V_{qs} &= R_{qs} i_{qs} + \frac{\mathrm{d}\varphi_{qs}}{\mathrm{d}t} + \omega_s \varphi_{ds} \end{aligned} \tag{1}$$

$$\begin{aligned} V_{dr} &= 0 = R_r i_{dr} + \frac{\mathrm{d}\varphi_{dr}}{\mathrm{d}t} - \left(\omega_s - \omega_r\right)\varphi_{qr} \\ V_{qr} &= 0 = R_r i_{qr} + \frac{\mathrm{d}\varphi_{qr}}{\mathrm{d}t} + \left(\omega_s - \omega_r\right)\varphi_{dr} \end{aligned} \tag{2}$$

The stator and rotor fluxes are expressed, respectively, by:

$$\begin{aligned} \varphi_{ds} &= L_s i_{ds} + L_m i_{dr} \\ \varphi_{qs} &= L_s i_{qs} + L_m i_{qr} \\ \varphi_{dr} &= L_r i_{dr} + L_m i_{ds} \\ \varphi_{qr} &= L_r i_{qr} + L_m i_{qs} \end{aligned} \tag{3}$$

For studying the dynamic behavior, the following equation of motion was added:

$$J \frac{\mathrm{d}\Omega_r}{\mathrm{d}t} = T_{em} - T_r - f_r \Omega_r \tag{4}$$

Where: J is the moment of inertia, f_r is the friction coefficient, T_{em} is the electromagnetic torque, T_r is the load torque.

Ω_r is the mechanical speed of the rotor.

The model of the IM has been completed by the expression of the electromagnetic torque T_{em} given below:

$$T_{em} = p\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \tag{5}$$

Where: p is the number of pole pairs.

III. DIRECT TORQUECONTROL WITH SOSMC

The classical DTC, proposed by [1], is based on the following algorithm:

i. Divide the time domain into periods of reduced duration $\boldsymbol{T_s}$.
ii. For each clock struck, measure the line currents and phase voltages of the IM.
iii. Reconstitute the components of the stator flux vector and estimate the electromagnetic torque, through the estimation of the stator flux vector and the measurement of the line current.
iv. The error between the estimated torque and the reference one is the input of a three level hysteresis comparator when this latter generates at its output the value of +1 to increase the flux and 0 to reduce it and thus increasing the torque -1 it reduce this flux and 0 to keep it constant in a band.
v. The error between the estimated stator flux magnitudes is the input of a two levels of the hysteresis comparator, which generates at its output the value +1 to increase the flux and 0 to reduce it.
vi. Select the state of the switches to determine the operating sequences of the inverter using the switching table.
vii. The input quantities are the stator flux sector and the outputs of the two-hysteresis comparators.
viii. The block diagram of the DTC of IM is shown in Fig. 1.

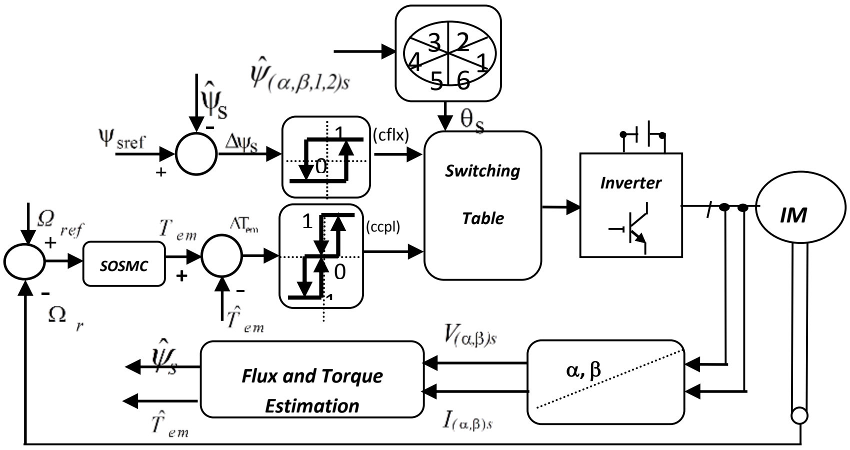

Figure1: Block diagram of the DTC with SOSMC of IM.

IV. CONCEPTION OF FITNESS FUNCTION

In the conception methods of GA-FSOSMC controller, among the criteria of performance the most known is the integration absolute error IAE which can be analytically estimated in the field of frequency as follows [22]:

$$IAE = \int_0^{\infty} |e(t)| dt \tag{6}$$

V. DESIGN OF FSOSMC-GA CONTROLLER

The optimization of scaling factors of the FLC using GA can be given by the input variable {e}, and the error change {ec} as follows:

$$e(t) = \Omega_{ref} - \Omega_r(t) \tag{7}$$

$$e_c(t) = \frac{de(t)}{dt} \tag{8}$$

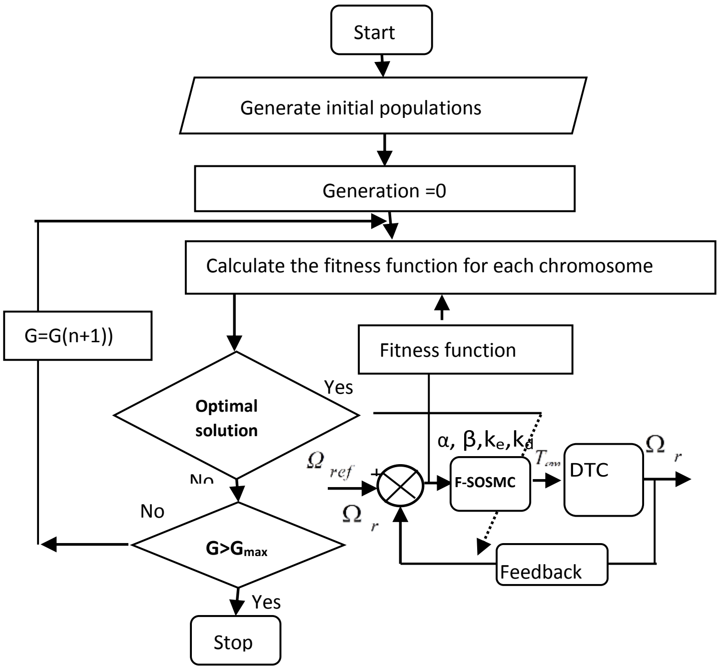

Figure2: Flowchart for fuzzy SOSMC-GA-DTC-IM

Table 1: Inference Rules.

ΔT_{em}		e_c						
		NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
e	**NB**	NB	NB	NB	NB	NM	NS	ZE
	NM	NB	NB	NB	NM	NS	ZE	PS
	NS	NB	NB	NM	NS	ZE	PS	PM
	ZE	NB	NM	NS	ZE	PS	PM	PB
	PS	NM	NS	ZE	PS	PM	PB	PB
	PM	NS	ZE	PS	PM	PB	PB	PB
	PB	ZE	PS	PM	PB	PB	PB	PB

1.1.1 Fuzzification

The inputs to the Fuzzy-GA have to be fuzzified before being fed into the control rule and gain rule determinations. The triangular membership functions (MFs) used for the input (e, e_c and, ΔT_{em}) are shown in Fig. 3 and Fig. 4.

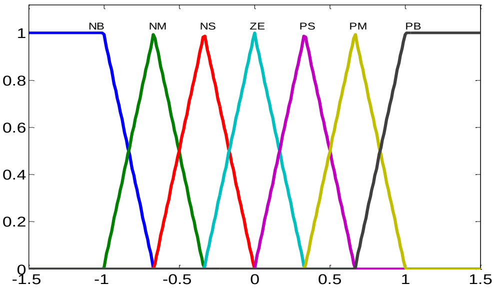

Figure3: Membership functions for e and e_c

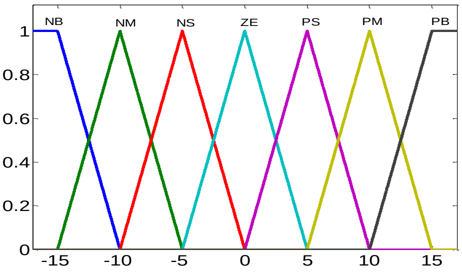

Figure4: Membership functions for $f_{\Delta}T_{em}$

1.1.2 Inference and Defuzzification

The present paper uses MIN operation for the calculation of the degree $\mu(\Delta T_{em})$ associated with every rule, for example, $\mu(\Delta T_{em})=\mathrm{Min}[\mu(e),\mu(e_c)]$.

In the defuzzification stage, a crisp value of the electromagnetic torque is obtained by the normalized output function as:

$$u=\frac{\sum_{j=1}^{m}\mu(\Delta T_{emj})\Delta T_{emj}}{\sum_{j=1}^{m}\mu(\Delta T_{emj})} \qquad (9)$$

where: m is the total number of rules (7*7), $\mu(\Delta T_{em})$ is the membership grade for the n rule, ΔT_{em} is the position of membership functions in rule n in U (-15,-10,-5,0,10,15), Figure. 5.

1.1.3 Control rule Determination

The logic of determining this rule matrix is based on a global knowledge of the system operation. As an example, we consider the following two rules:

If e is PB and e_c is PB then ΔT_{em} is PB
If e is ZE and e_c is ZE then ΔT_{em} is ZE

They indicate that if the speed is too small compared to its reference (e is PB), so a big gain (ΔT_{em} is PB) is required to bring the speed to its reference and if the speed reaches its reference and is established (e is ZE and e_c is ZE) so impose a small gain ΔT_{em} is ZE.

1.1.4 Fuzzy Second Order Sliding Mode Control

The proposed control strategy is based on the Super Twisting Algorithm. This algorithm is an exception that only requires information about the sliding surface [18] [19]. The application of this control strategy begins with the determination of the relative degree of the variable to be regulated. This variable is the speed, so we choose a surface that is sufficient to make the command appear. We define the following sliding surface [20] [21]:

$$S_{\Omega} = \Omega_{ref} - \Omega \tag{10}$$

$$\frac{d\Omega}{dt} = \frac{T_e - T_r - f_r\Omega}{J} \tag{11}$$

$$S^{*}{}_{\Omega} = \Omega^{*}{}_{ref} - \Omega^{*} = \Omega^{*}{}_{ref} - \frac{1}{J}\left(T_e - f\Omega_t - T_r\right) \tag{12}$$

If we define the functions A_{Ω} as follows:

$$A_{\Omega} = \Omega^{*}{}_{ref} - \frac{1}{J}\left(f_r\Omega - T_r\right) \tag{13}$$

$$s^{**}_{\Omega t} = A^{*}_{\Omega} - \frac{1}{J}T^{*}_{e} \tag{14}$$

Thus:

The second-order sliding mode controllers contain two parts:

$$I_{ref} = I_{eq} + I_N \tag{15}$$

Where: $I_N = I_1 + I_2$

$$\begin{aligned} I_1^{*} &= -\alpha_1\, fuzzy(S_{\Omega}) \\ I_2^{*} &= \beta_1 \left|S_{\Omega}\right|^{\rho}\, fuzzy(S_{\Omega}) \end{aligned} \tag{16}$$

To ensure convergence to zero in finite time, the gains can be chosen as follows:

$$\begin{cases} \alpha_1 > \dfrac{\phi}{\Gamma_{mi}} \\ \beta_1^2 \geq \dfrac{4\phi(\alpha_1 + \phi)}{T_e^2(\alpha_1 - \phi)} \\ 0 < \rho \leq 0.5 \end{cases} \tag{17}$$

Figure 5 illustrates the general structure of the FSOSMC-DTC of DSPMSM

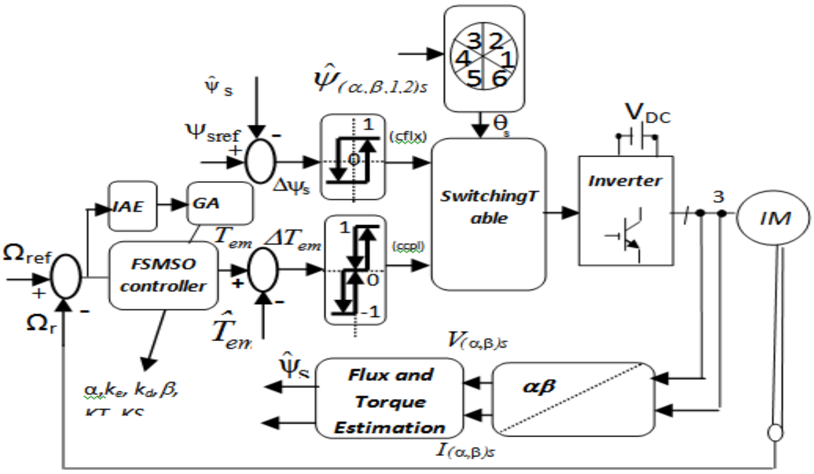

Figure5: Block diagram of the proposed DTC-FSOSMC-GA tuning speed controller

VI. SIMULATION RESULTS AND DISCUSSION

The results were obtained using a FSOSMC-GA algorithm programmed and implemented in MATLAB. The parameters of the IM are presented in appendix Table 3. To illustrate the performances of the direct torque control of the IM we replaced the classical PI controller by a fuzzy SOSMC-GA technique Fig. 5. The simulation is carried out under the following conditions: the hysteresis band of the torque comparator is set to ± 0.25 Nm and that of the flux comparator to ± 0.5 Wb.

Figure. 6 depicts the waveforms of the improved performances of speed control. We note that the use of the FSOSM-GA controller allows the speed to judiciously follow its reference value of 100 (rad/s) despite the presence of a load torque of 14 (N.m) at (t=1s). It represents a clear improvement in dynamic response with a hybrid controller, contrary to a drive with a standard DTC where the speed has underwent slightly rejected.

In Figure. 7 the electromagnetic torque produced by the IM which is controlled by DTC-SOSMC and DTC-fuzzy-SOSMC-GA is presented. In this figure, it can be noticed that the ripple is not the same for the two techniques. It is clear that the classical DTC-SOSMC present two problems, steady state error and high torque ripples. On the other hand, the DTC-fuzzy-SOSMC-GA corrects the steady state error and reduces the torque ripples.

In Figure. 8, it can be observed that the currents are sinusoidal and current ripples have also a notable reduction in fuzzy-SOSMC-GA controller compared to the standard controller.

Figure. 9 shows the trajectory of stator flux for the standard DTC and the hybrid DTC. It can be seen that this hybrid strategy has less ripple.

The parameters of GA algorithms are reported in Appendix Table 4.

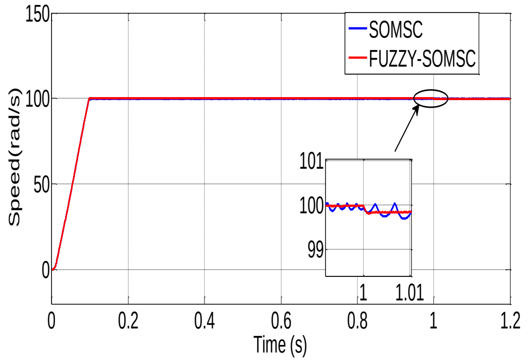

Figure6: Comparison of the rotor speed regulation of the DTC-SOSMC and hybrid DTC.

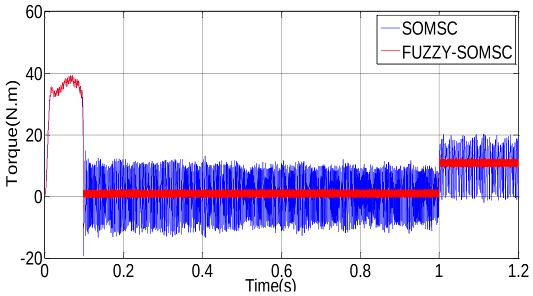

Figure7: Electromagnetic torque comparisons of the two strategies.

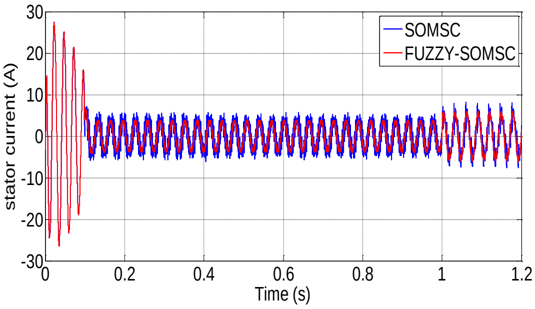

Figure8: Phase current for both hybrid DTC and classical DTC.

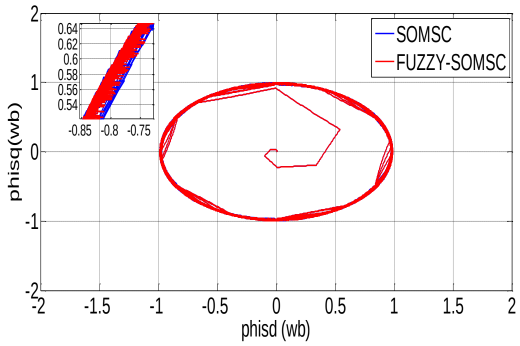

Figure9: Stator flux trajectory.

VII. ERROR TRACKING PERFORMANCE COMPARISONS

The three commonly used measures are Integral Squared Error (ISE), Integral Absolute Error (IAE) and Integral Time-weighted Absolute Error (ITAE), and are defined as:

$$\mathrm{ISE}=\int_0^T e_\Omega{}^2 dt \;;$$

$$\mathrm{ISE}=\int_0^T |e_\Omega| dt,$$

$$\mathrm{ISE}=\int_0^T t|e_\Omega| dt.$$

Where eΩ is the tracking errors for speed of DFIM.

Table 2 gives a quantitative comparison between the proposed fuzzy logic and the IP technique in load variation[23] .

Table 2: Performance error indexes comparison

Controller	**Error indexes**		
	IAE	**ISE**	**ITAE**
SMSO	6	237.556	296.912
Fuzzy-SMSOC-GA	0.3273	0.0536	0.0803

According to table 2 it is clearly shown that the proposed Fuzzy-SMSOC-GA controller has the smallest IAE, ISE and ITAE performance indexes with respect to SMSO controller. These results confirm the improved performance with the fuzzy-GA algorithm [23].

VIII. CONCLUSION

In this paper, a comparative study between the conventional DTC of the IM with SOSMC and DTC-fuzzy-SOSMC, GA has been presented for a speed controller. From the simulation studies, hybrid controller produced better performances in terms of a fast rise time, a small overshoot, reduced torque and flux ripples. Therefore, very satisfactory performances have been achieved. Furthermore, the effectiveness of the proposed algorithms is evaluated and justified from performance indices IAE, ISE and ITSE. According to the yielded simulation results, one can conclude that this algorithm is suitable for applications requiring a high tracking accuracy in presence of external disturbances.

IX. APPENDIX

Table 3: IM parameters [12]

Rated power	3KW
Stator resistance Rs1= Rs2	1.2Ω
Rotor resistance Rr	1.8Ω
Stator inductance Ls	0.1564H
Rotor inductance Lr	0.1564H
Mutual inductance Lm	0.15H
Pole pairs P	2
Machine inertia J	0.05 kg.m2
Viscous friction coefficient fr	0.001 kg.m2/s

Table 4: GA setup parameters.

Descriptions	Parameters
Population size	40
Maximum iteration	9
Crossover probability	0.8
Mutation probability	0.02
Initial range	[0 ; 1]

Table 5: Performance of SMSO controller.

KS optimized	KS =10.9387
KT optimized	KT=7.6184

Table 6: Performance of fuzzy -SMSO-GA controller.

Controller	**FSOSMC-GA**
Input scaling factor optimized KE	KE= 0.6218
Input scaling factor optimized KdE	KDE= 1
KS scaling factor optimized for the output	KS=2.2193
KT scaling factor optimized for the output	KT=2.5698

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