Journal of Fundamental and Applied Sciences

ISSN 1112-9867

Available online at http://www.jfas.info

Research Article

HYBRID FUZZY SECOND-ORDER SLIDING MODE CONTROL SPEED FOR DIRECT TORQUE CONTROL OF DUAL STAR INDUCTION MOTOR

B. Kiyyour*, D. Naimi, A. Salhi, L. Laggoune

Laboratory of electrical engineering Biskra, “LGEB”, University of Biskra, Algeria

Received: 07 May 2019 / Accepted: 03 August 2019 / Published online: 01 September 2019

ABSTRACT

This paper presents a Speed Fuzzy Second-Order Sliding Mode Control (FSOSMC) for Direct Torque Controlled Dual Star Induction Motor (DTC-DSIM). A DTC uses the instantaneous values of voltage vector where each reference voltage vector is computed with a DTC algorithm. The sliding mode control is characterized by its robustness against modeling disturbances and uncertainties; however, this technique has a major disadvantage which is the phenomenon of chattering that produces torque fluctuations. In order to overcome this drawback, a new control scheme that uses the FSOSMC for speed control is proposed. . It is shown that the proposed control strategy conserves the main advantages of the DTC in addition to reducing considerably the chattering effect. It is also robust against modeling disturbances and uncertainties. Several simulation tests are performed illustrating the high accuracy of the proposed control scheme.

Keywords: Dual star induction motor (DSIM). Direct torque control (DTC). Second-order sliding mode control (SOSMC). Speed fuzzy second-order sliding mode control (FSOSMC)

Author Correspondence, e-mail: bkiyyour@yahoo.fr

doi: http://dx.doi.org/10.4314/jfas.v11i3.27

1. INTRODUCTION

In large varieties of industrial applications, the growth of electrical energy consumption and high power electrical applications have caused problems at the level of the converter-machine assembly. In fact, the need of high switching frequencies and currents requires the use of high-gauge components. On the other hand, the machine windings must be designed to Support high voltages[1,2]. In order to meet the above-mentioned requirements, power segmentation is an appropriate solution while using multi-phase induction machines where the number of phases is greater than three supplied by one or more converters, For that reason, the multi-phase machines are more and more used for some high power industrial applications such as railway traction, ship propulsion and wind power systems. Among these multiphase drives. the dual star induction machines with two sets of three-phase stator windings, spatially shifted by 30 electrical degrees and isolated neutral points is one of the most widely discussed topologies[3,4].The DTC approach was firstly proposed by I.Takahashi[5]. It allows controlling the stator flux and electromagnetic torque from measurements of stator currents and voltages without the use of mechanical sensors. Moreover, this control strategy does not require flux decoupling nor pulse width modulation (PWM) to control the inverter. So, it is based on a direct determination of the switching control sequences applied to the voltage inverter. This choice is generally based on the use of hysteresis regulators whose function is to control the state of the system in order to obtain the amplitude of the stator flux and the electromagnetic torque. On the other hand, the use of the PI controller for the speed control has many disadvantages indeed these correctors are linear and cannot control non-linear systems with variable parameter[6].

Furthermore, when the controlled part is subjected to strong nonlinearities and time-variation, it is necessary to design control algorithms ensuring the robustness of the control strategy against model uncertainties parameters variations. The sliding mode control is one of these robust control methods[7-9]. It has undeniable advantages for the poorly identified systems with variable parameters. However, there are some problems like the chattering phenomenon, due to the discontinuous nature of the control. These disadvantages can be harmful for the motor, by heating up the windings or by exciting no modulated high frequency dynamics, indeed, depending on the frequency of this phenomenon; it can damage the power electronic components during switching. There are different methods to reduce the undesirable effects of this phenomenon, for instance: one can use a high order sliding modes whose principle is to reject the discontinuities at the level of the input system upper derivatives[10,11], thus, the chattering effect can be eliminated while keeping the control robustness characteristic and improving the accuracy of convergence. Furthermore and in order to improve the performance of this controller, we will combine it with fuzzy logic in order to form Fuzzy-Second Order Sliding Mode Controller (FSOSMC).

2. Dual Star Induction Motor Mathematical Model (DSIM)

The It is assumed that the DSIM is considered as an electromechanical system consisting of two three-phase stator windings, whose magnetic axes are displaced by an electrical angle of α =30° [1]. Figure 01 show the stator and rotor windings representation of DSIM.

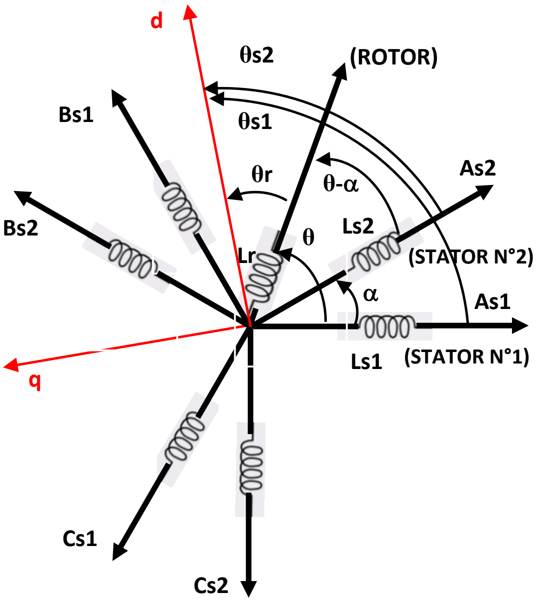


Fig.1. Windings scheme of DSIM

The general voltage equations for stator and rotor circuits can be presented in a matrix for as follows:

$$[V_{s1}] = [R_{s1}][L_{s1}] + \frac{d}{dt}[\phi_{s1}]$$

$$[V_{s2}] = [R_{s2}][L_{s2}] + \frac{d}{dt}[\phi_{s2}] \qquad (1)$$

$$0 = [R_r][L_r] + \frac{d}{dt}[\phi_r]$$

In the synchronous d-q reference frame, the system equation (1), can be rewritten as follow[13,14] :

$$v_{ds1} = R_s i_{ds1} + \frac{d\phi_{ds1}}{dt} - \omega_s \phi_{qs1}$$

$$v_{ds2} = R_s i_{ds2} + \frac{d\phi_{ds2}}{dt} - \omega_s \phi_{qs2} \qquad (2)$$

$$v_{qs1} = R_s i_{qs1} + \frac{d\phi_{qs1}}{dt} + \omega_s \phi_{ds1}$$

$$v_{qs2} = R_s i_{qs2} + \frac{d\phi_{qs2}}{dt} + \omega_s \phi_{ds2}$$

$$0 = R_r i_{dr} + \frac{d\phi_{dr}}{dt} - (\omega_s - \omega_r)\,\phi_{qr} \qquad (3)$$

$$0 = R_r i_{qr} + \frac{d\phi_{qr}}{dt} + (\omega_s - \omega_r)\,\phi_{dr}$$

Stator and Rotor flux components

$$\phi_{ds1} = L_{s1} i_{ds1} + L_m\,(i_{ds1} + i_{ds2} + i_{dr})$$

$$\phi_{qs1} = L_{s1} i_{qs1} + L_m\left(i_{qs1} + i_{qs2} + i_{qr}\right) \qquad (4)$$

$$\phi_{ds2} = L_{s2} i_{ds2} + L_m\,(i_{ds1} + i_{ds2} + i_{dr})$$

$$\phi_{qs2} = L_{s2} i_{qs2} + L_m\left(i_{qs1} + i_{qs2} + i_{qr}\right)$$

$$\phi_{dr} = L_r i_{dr} + L_m\,(i_{ds1} + i_{ds2} + i_{dr})$$

$$\phi_{qr} = L_r i_{qr} + L_m\left(i_{qs1} + i_{qs2} + i_{qr}\right) \qquad (5)$$

$$L_m = \frac{3}{2}\,L_{sr} = \frac{3}{2}\,L_{rs}$$

Lm: Cyclic mutual inductance between star 1, star 2 and rotor.

Where Ls1 = Ls2 is the stator leakage inductance of (d-q) equivalent circuit, and is mutual leakage inductance.

The electromagnetic torque of the motor can be expressed as the sum of two components caused by the electromagnetic interaction between the stator 1 and the rotor; and the interaction between the stator 2 and the rotor:

$$T_e = p\left(\phi_{ds1} i_{qs1} - \phi_{qs1} i_{ds1} + \phi_{ds2} i_{qs2} - \phi_{qs2} i_{ds2}\right) \qquad (6)$$

Mechanical equation:

$$J\frac{d\Omega}{dt} = T_e - T_r - k_f\Omega \quad (7)$$

3. Direct torque control of DSIM

The basic DTC scheme is shown in Figure 02. The DTC method is based on instantaneous space vector theory. By optimal selection of the space voltage vectors in each sampling period, the DTC achieves effective control of the stator flux and torque. Thus, the number of space voltage vectors and switching frequency directly influence the performance of DTC control system. The DTC requires accurate knowledge of the amplitude and angular position of the controlled flux with respect to the stationary stator axis in addition to the angular velocity for the torque control purpose. The principle of DTC operation also can be explained by analyzing the stator voltage equation in the stator flux reference frame[4,5].

For an effective torque control of the DSIM, it is imperative to adjust properly the flux, by putting ourselves in a fixed frame (α, β) related to the stator.

The expressions of stator voltages allow us to calculate, in real time and at any moment, the flux and torque magnitudes, using the following equations.

$$\phi_{S\alpha 1,2} = \int_0^t \left(V_{s\alpha 1,2} - R_{s1,2}\, i_{s\alpha,1,2}\right)dt \quad (8)$$

$$\phi_{S\beta 1,2} = \int_0^t \left(V_{s\beta 1,2} - R_{s1,2}\, i_{s\beta,1,2}\right)dt$$

Thus, the stator flux module is written:

$$\phi_S = \sqrt{(\phi_{S\alpha 1} - \phi_{S\alpha 2})^2 + \left(\phi_{S\beta 1} - \phi_{S\beta 2}\right)^2} \quad (9)$$

The angle θs is given by the following expression:

$$\theta_S = \mathrm{Arctg}\left(\frac{\phi_{S\alpha 1} + \phi_{S\alpha 2}}{\phi_{S\beta 1} + \phi_{S\beta 2}}\right) \quad (10)$$

The calculation of the stator flux is not sufficient to control the torque of the machine. In fact, a real-time torque estimation is required. Consequently, an expression of the torque was included in the program.

$$T_e = P.\left(\phi_{S\alpha 1}.i_{S\beta 1} + \phi_{S\alpha 2}.\phi_{S\beta 2} - \phi_{S\beta 1}.\ i_{S\alpha 1} + \phi_{S\beta 2}.i_{S\alpha 2}\right) \quad (11)$$

The error between the estimated and reference torques represents the input of a three level hysteresis comparator.

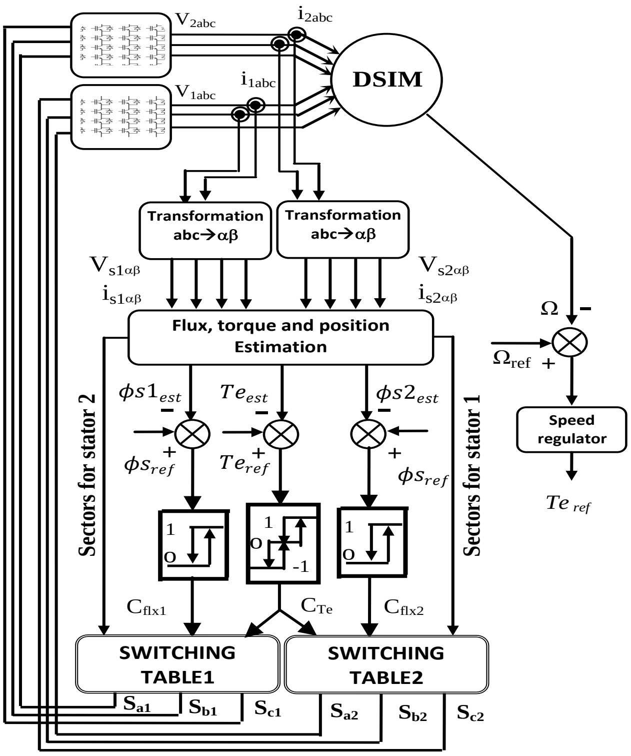


Fig.2. Direct torque control (DTC) scheme for DSIM

The aim of DTC for DSIM is to maintain the stator flux and torque within the limits of flux and torque hysteresis bands by a proper selection of the stator space voltage vectors during each sampling period (figure 03). The voltage vectors are selected according to the errors of stator flux and torque. Table 1 summaries the combined effects of each voltage vector on both stator flux and torque, assuming the stator flux is located in the first sector.

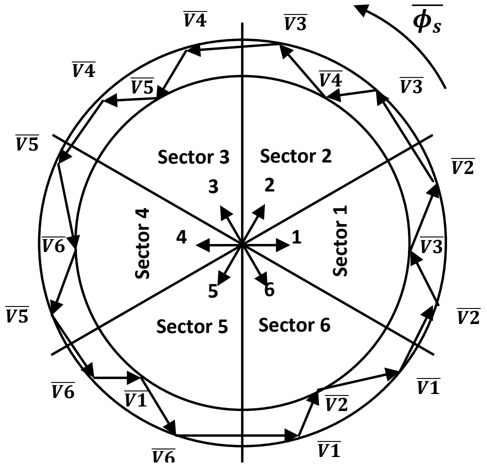


Fig.3. Rotation of startor flux linkage vector by voltage vector

Table 01. Switching Table Presented By Takahashi

Sector		**1**	**2**	**3**	**4**	**5**	**6**	**corrector**
Cflx=1	**c_{Te}=1**	V2	V3	V4	V5	V6	V1	**2 levels**
	c_{Te}=0	V7	V0	V7	V0	V7	V0	
	c_{Te}=-1	V6	V1	V2	V3	V4	V5	**3 levels**
Cflx=0	**c_{Te}=1**	V3	V4	V5	V6	V1	V2	**2 levels**
	c_{Te}=0	V0	V7	V0	V7	V0	V0	
	c_{Te}=-1	V5	V6	V1	V2	V3	V4	**3 levels**

4. Second Order Sliding Mode Control (SOSMC)

The aim of this section is to generate a second-order sliding regime on a surface S by cancellation of S and $\dot{S}$, (S = $\dot{S}$ = 0), this means that the system converges to zero at the intersection of S and $\dot{S}$ in the state space[10,14,22].

The main feature of this strategy is that the discontinuous part appears on the derivative of the V_{STI} control. Finally, when one calculates the system control $= \int \dot{u}$, it becomes continuous thus limiting the phenomenon of chattering. To achieve this goal, we use the algorithm of super-twisting, this algorithm applies only systems of relative degree 1 to avoid background noise. Its interest lies in the reduction of chattering, due to the continuity of the control signal[14,15,23]. The command law of the Super-Twisting is formed of two parts. The first V_1 is defined by its derivative with respect to time, while the second V_2 is continuous and according to the sliding variable[22,23].

$$V_{STI}(t) = V_1(t) + V_2(t)$$

Or
$$\begin{cases} \dot{V}_I(t) = -A\,sign(S) + V_2(t) \\ V_2(t) = -B|S|^{\delta}\,sign(S) \end{cases} \tag{12}$$

In finite time, the following conditions are given to ensure the convergence of slippery varieties [15-16]

$$A > \frac{\lambda}{k_m}$$

$$B^2 \geq \frac{4\lambda}{k_m^2}\frac{(A+\lambda)}{k_m(A-\lambda)} \tag{13}$$

$$0 < \delta < 0.5$$

5. Fuzzy Second Order Sliding Mode Controller (FSOSMC)

The use of sign function in SOSMC will cause a serious problem when the system state of the surface is close to the sliding surface [17-19], This undesirable effect can be reduced using the fuzzy second order sliding control FSOSMC, we combine the fuzzy logic with equivalent control (SOSMC), or we replace the sign function with inference fuzzy system Figure 04.

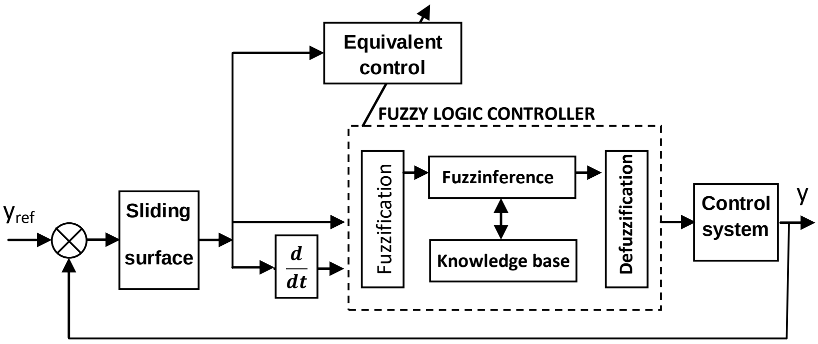


Fig.4. Structure of Fuzzy Second Order Sliding Mode Control

The membership functions of FSOSM-DTC are defined in Figure 05. The fuzzy rules base consists of collection of seven linguistic variables: negative big (NB), negative medium (NM), negative small (NS), equal zero (EZ), positive small (PS), positive medium (PM) and positive big (PB). The details of fuzzy rules are shown in Table 3.

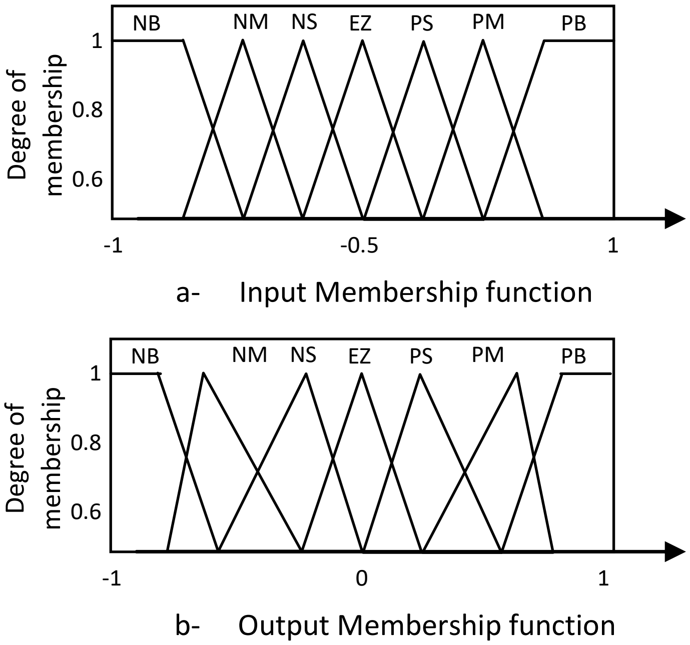


Fig.5. Input and output Membership functions

6. Simulation Results and Discussions

Enter In order to study the importance of the Fuzzy Second Order Sliding Mode Controller, simulation models are built using Matlab/Simulink. Two control schemes are implemented using the same implementation conditions, the DTC-FSOSMC with an FSOSMC controller and the classical DTC (C-DTC) with a classical PID controller. The parameters of the DSIM are presented in Table 4.

Figures 06 and 07 show the speed and the electromagnetic torque of the two systems when applying a load torque, at t = 0.7s with a torque of 14N.m then at 1.7s by -14Nm while the reference flux is kept as ϕf = 1.3Wb.

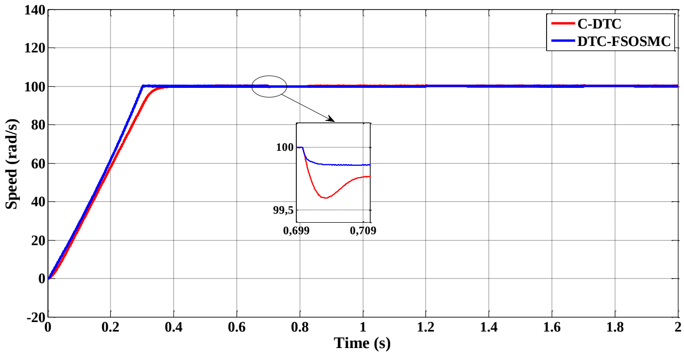


Fig.6. Comparison between speed response for DTC-FSOSMC and C-DTC

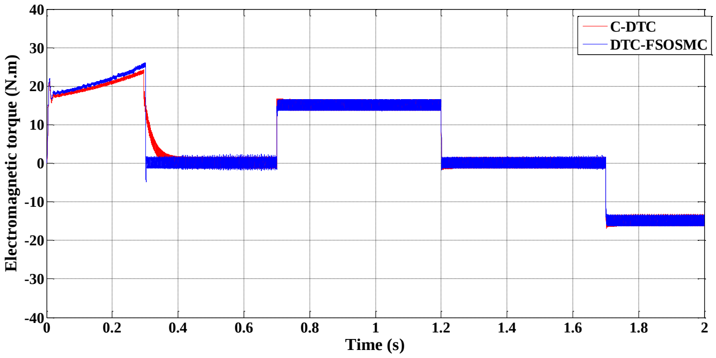


Fig.7. Electromagnetic torque Comparison of DTC-FSOSMC and C-DTC

The simulation results illustrate both the steady state and transient performance of the DTC, the controlled torque and flux will follow perfectly their reference curves in both transient and steady states. The waveforms depicts that the two systems give good results with remarkable superiority for the DTC-FSOMSC, the performance of the latter represents a significant improvement in the dynamic response of the two quantities, speed and torque with faster convergence: faster rise time, shorter stabilization time, and excellent dynamic performance of torque and flux control (Figures 06-11).

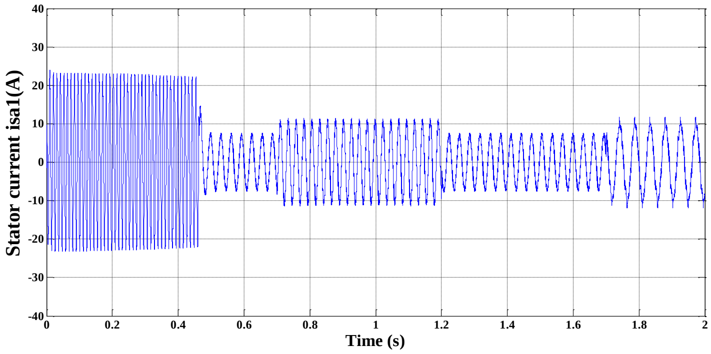


Fig.8. Shape of the phase current in the stator 1 for DTC-FSOSMC

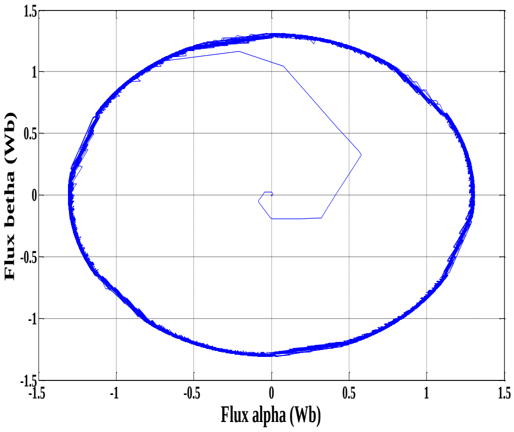


Fig.9. Stator flux circular trajectory of DTC-FSOSMC

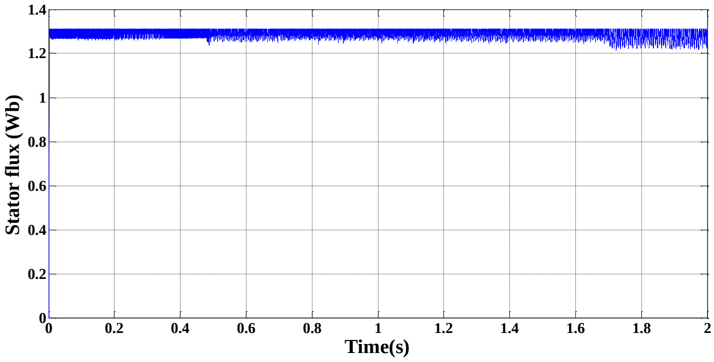
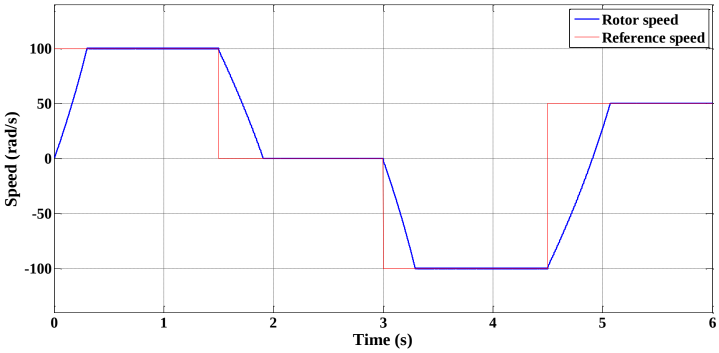


Fig.10. Stator flux magnitude response of DTC-FSOSMC

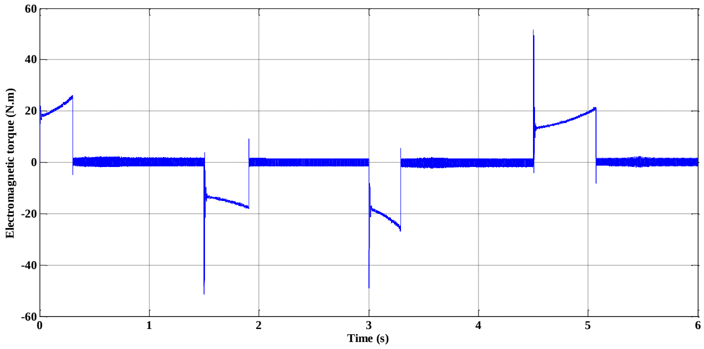
Figures 8, 9 and 10 show the first-phase stator current isa1 and the phase flux of the DTC-FSOSMC with a reference flux at 1.3Wb.

The waveform of the stator current is closed to a sinusoidal signal and the flux properly follows its reference even with the presence of load.

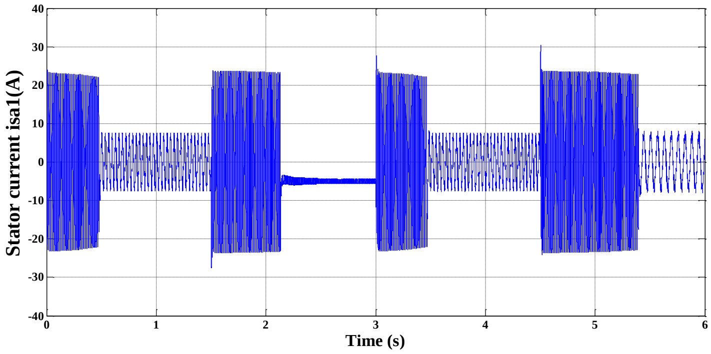
To test the robustness of the FSOSMC controller, a speed reversal test was completed.



(a) Rotor speed



(b) Electromagnetic torque



(c) Phase current in the stator 1

Fig.11. Simulated responses for reference speed reversal with no load

Figure 11 shows the curves of speed, torque and stator current (isa_1), it is clear that the speed follows perfectly its reference, it generates an increase in the current of a magnitude identical to that observed during the transient regime initial, which stabilizes and gives rise to sinusoidal forms of constant amplitude.

To evaluate the performance of the DTC-FSOSMC and DTC-PID control system, we adopt a performance index, such as the integral of the absolute error (IAE), the integral of time multiplied by the error squared (ITSE), integral square error (ISE) and the integral of the time multiplied by the absolute value of the error (ITAE).

The monitoring performance of the controllers is presented in Table 2.

Table 2. Comparison of performance index

Performance index	IAE	ISTE	ISE	ITAE
C-DTC	25.51	220.9	1753	4.221
DTC-FSOSMC	18.55	116.9	1279	2.26

8. CONCLUSION

In this paper, direct torque control method of DSIM with a speed fuzzy second-order sliding mode controller (FSOSMC) is presented, the simulation results show the robustness and good performance of the proposed DTC-FSOSMC over the conventional DTC- PID (a small response time, overtaking negligible, a small speed inversion time). Furthermore the performance of the proposed techniques is evaluated and justified on the basis of performance indices IAE, ITSE, ISE and ITAE.

Appendix:

Table 3. Fuzzy rules

de e	Ne3	Ne2	Ne1	Ze	Pe1	Pe2	Pe3
Nde3	NB	NB	NB	NB	NM	NS	Z
Nde2	NB	NB	NB	NM	NS	Z	OS
Nde1	NB	NB	NM	NS	Z	OS	PM
Zde	NB	NM	NS	Z	OS	PM	PB
Pde1	NM	NS	Z	OS	PM	PB	PB
Pde2	NS	Z	OS	PM	PB	PB	PB
Pde3	Z	PS	PM	PB	PB	PB	PB

Table 4. Parameters of Dual Star induction Motor

Stator resistances Rs1=Rs2	3.72 Ω
Rotor resistance Rr	2.12Ω
Stator inductances Ls1=Ls2	0.022H
Rotor inductance Lr	0.006H
Mutual inductance Lm	0.3672H
Moment of inertia J	0.0662Kg.m2
Friction coefficient k_f	0.001**N**.m.s/rad

6. REFERENCES

[1] Hadiouche D, Razik H and Rezgzou A. On the modeling and design of dual-stator windings to minimize circulating harmonic currents for VSI fed AC machines. IEEE Trans. Indus Appl., 2004, 40(2), 506-515

[2] Pieńkowski K. Analysis and control of dual stator winding induction motor. archives of electrical engineering.,2012, 61(3), 421-438

[3] Levi E. Multiphase electric machines for variable-speed applications. IEEE Transactions on industrial electronics, 2008, 55(5), 1893-1909

[4] Takahashi I,Noguchi T. A New Quick-Response and high Efficiency Control Strategy of an Induction Motor. IEEE Trans. on IA, 1986, 22(5)

[5] Vas P. Sensorless Vector and Direct Torque Control, Oxford university press, New york USA, 1998

[6] Oliveira C M R., Aguiar M L, Monteiro J B A, Pereira W C, Paula G T and Santana M P. Vector control of induction motor using a sliding mode controller with chattering reduction. *2015 IEEE 13th Brazilian Power Electronics Conference and 1st Southern Power Electronics Conference (COBEP/SPEC)*, Fortaleza, 2015, 1-6

[7] Zadehbagheri M , Ildarabadi R and Baghaei Nejad M. Sliding Mode Control of a Doubly-fed Induction Generator (DFIG) for Wind Energy Conversion System. International Journal of Scientific & Engineering Research, 2013, 4(11)

[8] Liu Y, Wang Z, Xiong L, Wang J, Jiang X, Bai G, Li R and Liu S. DFIG wind turbine sliding mode control with exponential reaching law under variable wind speed. International Journal of Electrical Power & Energy Systems, 2018, Volume 96, 253-260

[9] Xiong L, Li P, Li H and Wang J. Sliding Mode Control of DFIG Wind Turbines with a Fast Exponential Reaching Law. Energies, 2017, 10(11):1788

[10] Bartolini G, Ferrara A,Levant A and Usai E. Lecture Notes in Control and Information Sciences, Springer, London, 1999, vol 247, doi.org/10.1007/BFb0109984

[11] Guillermo J R, Cañedo J M, Loukianov A G and Reyes J M., 2011, IFAC Proceedings Volumes 44(1), 3938-3943

[12] Ziane D,Azib A, Taib N and REKIOUA T. Study and Design of the direct torque control of Double star induction motor, Journal of Electrical Systems,2013, 114-124

[13] Kundrotas B, Lisauskas S and Rinkeviciene R. Model of Multiphase Induction Motor, Electronics and Electrical Engineering. – Kaunas: Technologija., 2011, 5(111), 111–114

[14] Levant A. Sliding order and sliding accuracy in sliding mode control, International Journal of Control., 1993,58(6), 1247–1263

[15] Lin W B and Chiang H K. Super-Twisting Algorithm Second-Order Sliding Mode Control for a Synchronous Reluctance Motor Speed Drive. Mathematical Problems in Engineering, vol. 2013, doi: 10.1155/2013/632061.

[16] Boudjema Z, Taleb R, Djeriri Y and Yahdou A. A novel direct torque control using second order continuous sliding mode of a doubly fed induction generator for a wind energy conversion system. Turkish Journal of Electrical Engineering & Computer Sciences, 2017, 965 – 975

[17] Benkahla M, Taleb R and Boudjema Z. . Electrical Engineering & Electromechanics. 2018, 11-19, doi : 10.20998/2074-272X.2018.4.02

[18] Yuan X , Chen Z , Yuan Y , and Huang Y. Design of fuzzy sliding mode controller for hydraulic turbine regulating system via input state feedback linearization method. Energy, 2015, 93, 173–187

[19] Meroufel S, Massoum A, Bentaallah A and Wira P. Double star induction motor direct torque control with fuzzy sliding mode speed controller, Rev. Roum. Sci. Techn. Electrotechn. et Energ. 2017, 31–35..

[20] Yuan X, Chen Z, Yuan Y and HuangY. Design of fuzzy sliding mode controller for hydraulic turbine regulating system via input state feedback linearization method. *Energy*, 2015, 173-187

[21] Kairous D and Belmadani B. International Journal of Advanced Computer Science and Applications, 2015, 6(8).167-175, DOI : 10.14569/IJACSA

[22] Eker I. Second-Order Sliding Mode Control with PI Sliding Surface and Experimental Application to an Electromechanical Plant,Arab J Sci Eng, 2012, 1969–1986.

How to cite this article:
Kiyyour B, Naimi D, Salhi A, Laggoune L. Hybrid fuzzy second-order sliding mode control speed for direct torque control of dual star induction motor. J. Fundam. Appl. Sci., 2019, *11(3), 1440-1454.*