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Modeling, Design & Simulation of Fuzzy Logic Control to Improve Direct Torque Control of Double Star Induction Motor

***Abstract**. All the studies and articles on the DTC control system talk about its shortcomings and the problems resulting from the use of hysteresis controllers. It results in strong ripples in torque, steady flow and constant current. Moreover, it is difficult to adjust the sensitivity to parametric variables due to the use of PI controllers due to the complexities of the system. To overcome these drawbacks and through this article, DTC control is designed on Double Star Induction Motor (DSIM), and through experiments it showed us some problems caused by hysteresis. Advantages can also be used of artificial intelligence techniques like fuzzy logic, fuzzy control is a way to control a system without needing to know its mathematical model of the system. To this end, It is through the advantages of fuzzy logic that it has been applied in this article to the application of DTC control, which is called Fuzzy Direct Torque Control (FDTC). Where we have replaced hysteresis controllers and switch tables with fuzzy logic switch controllers. We also simulated it by MATLAB/SIMULINK and compared the results obtained between a conventional DTC and a DTC using fuzzy logic and it is shown that the proposed FDTC method can significantly reduce torque ripples and is suitable for different motors under operating conditions.*

***Streszczenie.** Wszystkie opracowania i artykuły dotyczące układu sterowania DTC mówią o jego wadach i problemach wynikających ze stosowania regulatorów histerezowych. Powoduje to silne tętnienia momentu obrotowego, stały przepływ i stały prąd. Ponadto trudno jest dostosować czułość na zmienne parametryczne ze względu na zastosowanie regulatorów PI ze względu na złożoność systemu. Aby przezwyciężyć te wady, w tym artykule zaprojektowano sterowanie DTC w silniku indukcyjnym z podwójną gwiazdą (DSIM), a eksperymenty wykazały pewne problemy spowodowane histerezą. Można również wykorzystać zalety technik sztucznej inteligencji, takie jak logika rozmyta, sterowanie rozmyte to sposób na sterowanie systemem bez konieczności znajomości jego matematycznego modelu systemu. W tym celu właśnie dzięki zaletom logiki rozmytej zastosowano ją w tym artykule do zastosowania sterowania DTC, zwanego Fuzzy Direct Torque Control (FDTC). Gdzie zastąpiliśmy sterowniki histerezy i tablice przełączające sterownikami przełączającymi z logiką rozmytą. Przeprowadziliśmy także symulację za pomocą MATLAB/SIMULINK i porównaliśmy wyniki uzyskane pomiędzy konwencjonalnym kodem DTC a kodem DTC przy użyciu logiki rozmytej i wykazano, że proponowana metoda FDTC może znacznie zmniejszyć tętnienia momentu obrotowego i jest odpowiednia dla różnych silników w warunkach pracy. (**Modelowanie, projektowanie i symulacja sterowania rozmytego w celu poprawy bezpośredniego sterowania momentem obrotowym silnika indukcyjnego z podwójną gwiazdą**)*

Keywords: Double Star Induction Motor (DSIM), Direct Torque Control (DTC), Fuzzy Logic Controller (FDTC), Switching Table (ST).
Słowa kluczowe: Silnik indukcyjny z podwójną gwiazdą (DSIM), bezpośrednie sterowanie momentem obrotowym (DTC).

Introduction

The Double Star Induction Motor (DSIM) has simple structure, good performance, ruggedness and reliability, easy maintenance and low cost [1,2], which can provide solutions for various industrial fields requiring high performance, suchas: l hybrid vehicles, traction and propulsion locomotives for ships and other applications requiring safety conditions such as pumps, fans, compressors, rolling mills, cement works, mining winches [3,4].However, the machine is difficult to control because it has a strong nonlinear coupling system with fast dynamics and time-varying parameters [5].

These restrictions need more developed control algorithms for the control of the motor torque and flux in the real time. Many solutions have been created in this regard. Various strategies have been proposed to control the literature to achieve this goal. By the mid-1980s, a control strategy called Direct Torque Control or DTC (Direct Torque Control) appeared to be competing with traditional schemes. This control strategy was introduced by TAKAHASHI [6] and M. DEPENBROCK [7]. Direct torque control has several advantages such as simplicity, fast response and low parameters sensitivity [8]. The Park transformation is not required in this control scheme.It allows robust, direct and independent flux and electromagnetic torque controlby selecting an optimal switching vector. It presents a good dynamics performances [9 10]. However, the mains drawbacks of this control strategy are: high torque ripples, variable switching frequency, acoustic noise and mechanical vibrations. These drawbacks are caused by the use of hysteresis controllers. Thus, the output power quality degrades due to switching losses and current distortion due to variable switching frequency. Low speed problem due to neglect of Star resistance [11].

In order to get out of these problems and improve DTC, many improvements technologies have been developed. Generally, there are two key strategies for reducing torque ripple. The first is to use multi-level inverters that can provide low ripples and more precise flux and torque control [12]. However, due to the high number of levels, in this strategy the power structure is more expensive and the control is more complicated. Therefore, this method is particularly suitable for high-performance applications [13]. The second solution is the use of Space Vector Modulation, where it solves the most common drawbacks of DTC (i.e. high flux and torque ripple). Due to the use of a synchronous frame (non-stationary frame), the control scheme is complex and requires a transformation of the coordinates of the axes [14]. Furthermore, these modified control schemes, where SVM-DTC uses linear proportional-integral (PI) to generate the voltage reference in (d-q), may affect the robustness of the overall control system. Due to the frame controller its dynamics and stability are very sensitive to different uncertainties, parameter fluctuations and external disturbances [15,16]. An advanced control strategy used fuzzy logic for DTC of double star induction motor (DSIM) is applied and this is to improve DTC performance and overcome the above issues. Due to the advantages of artificial intelligence technologies such as fuzzy logic, neural network and neuro-fuzzy,…etc. In fact, fuzzy control is a method of controlling a system without knowing the mathematical model of the system. Fuzzy control is known to work equally well for complex nonlinear multidimensional systems [11].Fuzzy logic is the most basic control intelligent algorithm and doesn't require a complex mathematical analysis[12,17]. To this end, the basic advantages of DTC control and fuzzy logic are combined in a control strategy called Fuzzy Direct Torque Control (FDTC). In this control strategy, DTC based on fuzzy logic can achieve high performance [18]. The features of direct torque control and fuzzy logic are merged in this proposed control technique.

The article is organized as follows: We will start with the introduction, the modeling of the double star induction motor (DSIM) is presented in Part II. We will discuss traditional DTC techniques based on the use of hysteretic controllers and switch tables in Part III. In the fourth part, which is the most important one we have worked on, we will implement a DTC using two controllers based on fuzzy logic. Obtaining the simulation results from what has been studied using the MATLAB/SIMULINK environment, presenting them, analyzing them and comparing them will be in the fifth part.

Finally, we get the conclusions and suggestions for future work, which will be presented in the sixth part.

Double Star Induction Motor Model

The double star machine (DISM) is a very complex nonlinear system. This machine can be well controlled in different working modes. We use the most suitable model, i.e. the study of dynamic behavior and the design of the DSIM control algorithm, which is a two-step model represented by the reference (α, β) [11,19].

The complexity of three-phase representation (a, b, c) can be reduced using this model. Mathematical model of a machine in an (α, β) coordinate system (a fixed coordinate system).

It can be written with the following set of electrical/mechanical equations are the first and second stars [20, 21], respectively:

1) Electrical equations

(1) $$V_{s1,\alpha\beta} = R_{s1}.I_{s1,\alpha\beta} + L_{s1}.\frac{d}{dt}\left(\Phi_{s1,\alpha\beta}\right)$$

(2) $$V_{s2,\alpha\beta} = R_{s2}.I_{s2,\alpha\beta} + L_{s2}.\frac{d}{dt}\left(\Phi_{s2,\alpha\beta}\right)$$

(3) $$R_r.I_{r,\alpha\beta} + L_r.\frac{d}{dt}\left(\Phi_{r,\alpha\beta}\right) = 0$$

Where: $V_{s1,\alpha\beta}, V_{s2,\alpha\beta}$: Star voltages α β components; $V_{s1,\alpha\beta}, V_{s2,\alpha\beta}$: Star and Rotor currents α β components; $\Phi_{s1,\alpha\beta}, \Phi_{s2,\alpha\beta}, \Phi_{r,\alpha\beta}$: Star and Rotor flux α β component.

2) Magnetic equations

The flux equations are written as follows [20]:

(4) $$\Phi_{s1,\alpha\beta} = L_{s1,\alpha\beta}.+L_m.(I_{s1,\alpha\beta}+I_{r,\alpha\beta})$$

(5) $$\Phi_{s2,\alpha\beta} = L_{s2,\alpha\beta}.+L_m.(I_{s2,\alpha\beta}+I_{r,\alpha\beta})$$

(6) $$\Phi_{r,\alpha\beta} = L_{r,\alpha\beta}.+L_m.(I_{(s1,s2),\alpha\beta}+I_{r,\alpha\beta})$$

We consider:

L_m: Cyclic mutual inductance between star (1,2), and rotor.

$L_{s1,s2,r}$: The inductance of a stator (1,2), and rotor respectively.

2) Mechanical equation

Mechanical equations are written in the form [22, 23]:

(7) $$T_e = T_r + \frac{K_f}{p}\omega_r + \frac{J}{p}\dot{\omega}_r$$

The electromagnetic moment, through the flux and currents of the rotor, can also be formulated as follows [1]:

(8) $$T_e = p\frac{L_m}{L_m+L_r}.\left[\Phi_{r\alpha}\left(i_{s1\beta}+i_{s2\beta}\right)-\Phi_{r\beta}\left(i_{s1\alpha}+i_{s2\alpha}\right)\right]$$

Direct torque control

Figure.1 shows the basic direct torque control scheme.

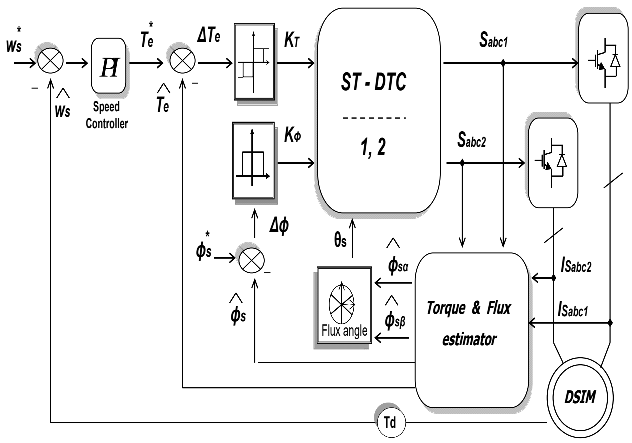


Fig. 1. Schematic diagram for direct torque control.

From the output of the switching table, we obtain the Star voltage of the switching states (Sa, Sb and Sc) and the constant voltage Udc [19,] of the junction created by the switching table, which are obtained by:

(9) $$\begin{bmatrix} V_{ak} \\ V_{bk} \\ V_{ck} \end{bmatrix} = \frac{U_{dc}}{3}.\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}.\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix}$$

With: $k = 1,2$.; V_{a1b1c1}, V_{a2b2c2}: Star voltages; S_a, S_b and S_c: Switching logic states (0 or 1); U_{dc}: DC bus voltage

He set of voltage vectors provided by each two-level voltage inverter is shown in Figure 2.

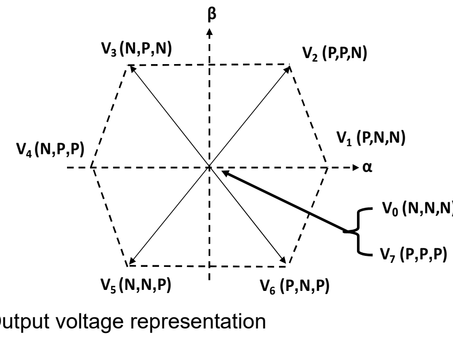


Fig. 2. Output voltage representation

While the Star current is measured, which is given by from the following equation [15]:

$$(10)\quad \begin{cases} I_{sk,\alpha} = \sqrt{3/2}.I_{ak} \\ I_{sk,\beta} = 1/\sqrt{2}.\left(I_{ak} + 2.I_{bk}\right) \end{cases}$$

With: k=1, 2.; $I_{s1,\alpha\beta}, I_{s2,\alpha\beta}$:Star currents αβ components.

The conversion from a three-phase reference (a, b, c) to a two-phase reference (α, β) is done by the concordia transformation. And from it we get the two-star voltage vector expressions for the double-star induction machine in the following form:

The following equation shows how this transformation is obtained [24, 25] :

the first star: $\left[V_{s1,\alpha\beta}\right] = \left[P(0)\right].\left[V_{a1b1c1}\right]$.

$$(11)\quad \begin{bmatrix} V_{s1\alpha} \\ V_{s1\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} . \begin{bmatrix} V_{a1} \\ V_{b1} \\ V_{c1} \end{bmatrix}$$

the second star: $\left[V_{s2,\alpha\beta}\right] = \left[P(-\delta)\right].\left[V_{a1b1c1}\right]$

in our cas $\delta = -30^{\circ}$.

$$(12)\quad \begin{bmatrix} V_{s2\alpha} \\ V_{s2\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sqrt{3}/2 & \sqrt{3}/2 & 0 \\ 1/2 & 1/2 & -1 \end{bmatrix} . \begin{bmatrix} V_{a2} \\ V_{b2} \\ V_{c2} \end{bmatrix}$$

With : $V_{s1,\alpha\beta}, V_{s2,\alpha\beta}$:Star voltages αβ components.

From the voltage and current in the reference frame (α, β), the magnitude of the magnetic flux can be calculated using the following equation

$$(13)\quad \Phi_{S1,\alpha\beta} = \int_0^t \left(V_{S1,\alpha\beta} - R_{S1}.I_{S1,\alpha\beta}\right).dt$$

$$(14)\quad \Phi_{S2,\alpha\beta} = \int_0^t \left(V_{S2,\alpha\beta} - R_{S2}.I_{S2,\alpha\beta}\right).dt$$

Where : $\Phi_{s1,\alpha\beta}, \Phi_{s2,\alpha\beta}$:Star flux αβ components

Thus, the magnitude and the phase of Star flux is defined by [22]:

$$(15)\quad \left|\Phi_{S1,2}\right| = \sqrt{\Phi^2_{s\alpha1,2} + \Phi^2_{s\beta1,2}}$$

$$(16)\quad \theta_{s1,2} = \text{arctg}\left(\frac{\Phi_{s\beta1,2}}{\Phi_{s\alpha1,2}}\right)$$

Torque and flux will be calculated by reference to the reference system for current and voltage (α, β), and we write the equation in the form[1] :

$$(17)\quad \hat{T}_{e1,2} = p.\left(\Phi_{s\alpha1,2}.I_{s\beta1,2} - \Phi_{s\beta1,2}.I_{s\alpha1,2}\right)$$

In which :

$$\hat{T}_e = \hat{T}_{e1} + \hat{T}_{e2}$$

$$(18)\quad \hat{T}_e = p[\Phi_{s1\alpha}.i_{s1\beta} + \Phi_{s2\alpha}.i_{s2\beta} - \Phi_{s1\beta}.i_{s1\alpha} - \Phi_{s2\beta}.i_{s2\alpha}]$$

The reference value is then compared to an estimate of torque or flux, and the result of the comparison forms the input to the hysteresis comparator. The resulting error is fed to a two-stage hysteresis comparator for flux and a three-stage hysteresis comparator for torque, allowing the motor to be controlled in either direction of rotation [11, 26]

$$(19)\quad \begin{cases} \varepsilon_{Te} = T_e^* - \hat{T}_e = \Delta T_e \\ \varepsilon_{\Phi} = \Phi^* - \hat{\Phi} = \Delta\Phi_s \end{cases}$$

When we get the logical value from the deceleration block output for both the torque and flux, and also get the angle θs. We can construct the classic Takahashi sequence table of electromagnetic torque and flux. As shown in the table 1 [17] :

Table 1. Takahashi and Noguchi switching table.

		θs					
		θ1	θ2	θ3	θ4	θ5	θ6
ΔΦs	ΔTe	Voltage Vector					
1 (P)	1(P)	P P N	N P N	N P P	N N P	P N P	P N N
	0(Z)	P P P	N N N	P P P	N N N	P P P	N N N
	-1(N)	P N P	P N N	P P N	N P N	N P P	N N P
0 (N)	1 (P)	N P N	N P P	N N P	P N P	P N N	P P N
	0 (Z)	N N N	P P P	N N N	P P P	N N N	P P P
	-1 (N)	N N P	P N P	P N N	P P N	N P N	N P P

Direct Torque Control Using Fuzzy Logic

Fuzzy Direct Torque Controller (FDTC)

Figure 3 shows the block diagram adopted for Double-star fuzzy DTC control (DSIM), the concept of the controller is the same as in the case of traditional DTC. Two fuzzy logic controllers were used to replace the traditional switch table and hysteresis [5,27] controllers. This is for better control performance.

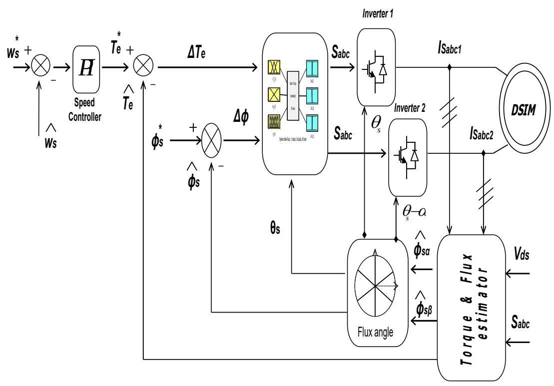


Fig. 3. Block diagram DTC with fuzz applied to DSIM.

Principe of Fuzzy direct control

Fuzzy controller is designed with three fuzzy state variables, namely torque error ΔTe, flux error ΔΦs and flux angle θs, which are considered as inputs to each fuzzy logic controller, and the output variables are decomposed into three sub- The outputs represent three switches (S_a, S_b, S_c) representing the switching of the inverter on two levels or a selected voltage vector [17, 27]

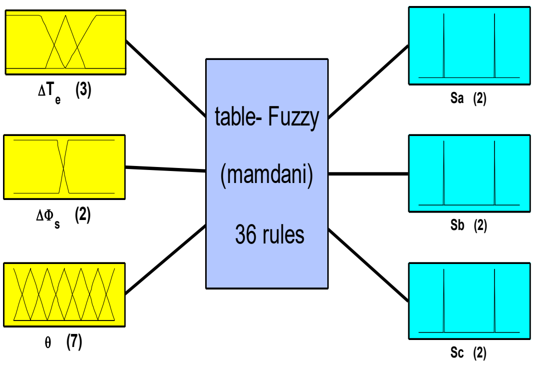


Fig. 4.Flow Diagram For Fuzzy Logic Switching Controller.

Inputs fuzzification

1) Electromagnetic torque error membership

Equation 20, is related to the electromagnetic torque error variable, which is the first variable. It relates to the reference value as well as the estimated torque (*Te_ref* and *Te*). [26]

(20) $$\Delta T_e = T_e^* - \hat{T}_e$$

The membership function of the electromagnetic torque error is given by three linguistic terms: negative (N), zero (Z), and positive (P), as shown in Figure 1.

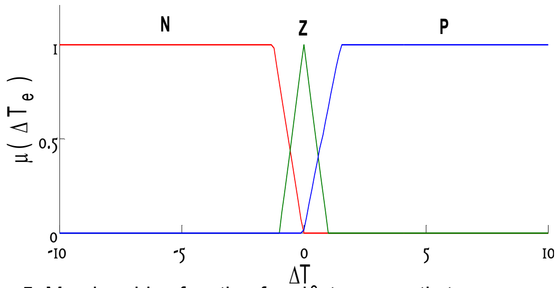


Fig. 5. Memberships function for electromagnetic torque error.

We will define for the two fuzzy groups (P, N) a trapezoidal membership, and also for the fuzzy group (Z) a trigonometric membership

2) Flux linkage error

Equation 21, is related to the flux error variable, which is the second variable. Relates to the reference value and the estimated value of the flux [28].

(21) $$\Delta\Phi_s = \Phi_s^* - \hat{\Phi}_s$$

The membership function of the Star flux linkage error is given by two terms: positive (P), negative (N), as shown in Figure 6. Which allows us to choose the two fuzzy groups (P) and (N) related to the trapezoidal membership functions.

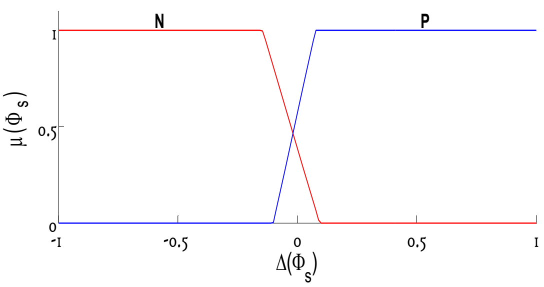


Fig. 6. Memberships function for flux error.

3) Angle of flux linkage (*θS*)

The position of the star flux is the third input variable, the angle θs between the reference system (α, β) and the vector Φs is given by the following relation [29]

(22) $$\theta_{s(1,2)} = \arctan g \frac{\Phi_{\beta s(1,2)}}{\Phi_{\alpha s(1,2)}}$$

Figure 07, shows membership functions for the six groups (θ_1. θ_6), so that the membership function can be chosen in the form of triangles for all six angles θ_i.

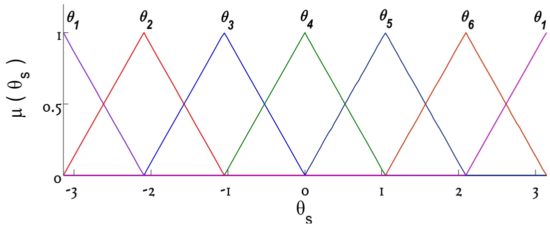


Fig. 7. Memberships function for flux position.

Outputs fuzzification

The output is represented by fuzzy groups, which need to be converted to non-fuzzy output according to certain methods. However, the system gives us three sub-outputs (Sa, Sb, Sc), due to the mysterious controller that divides the output variable [29].

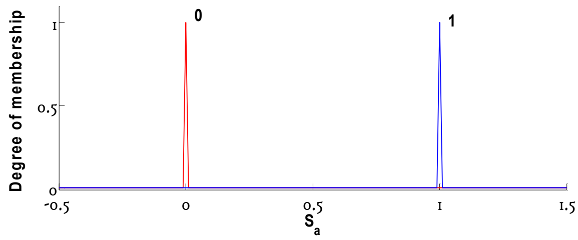


Fig. 8. Output variables (Sa).

The discourse space for each output is split into two fuzzy sets (zero and one) whose membership functions are by type forms shown in Figure 8.

Control rules

Figure 9, shows the architecture of the fuzzy console, composed of database, rule base, and defuzzification blocks and decision making. The rule base is where all the fuzzy rules are stored, and the latter specifies the output variables of the controller from the input variables, as shown in Table 1[30].

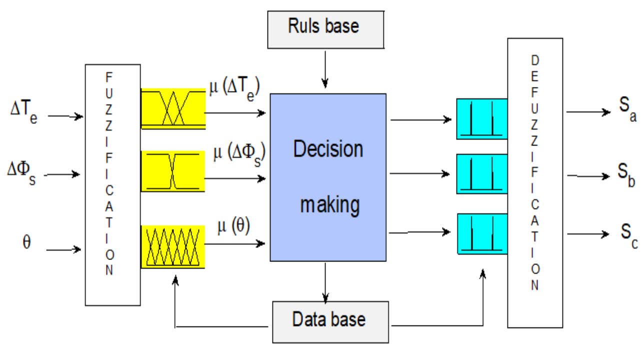


Fig. 9.Flow Diagram For Fuzzy Logic Switching Controller.

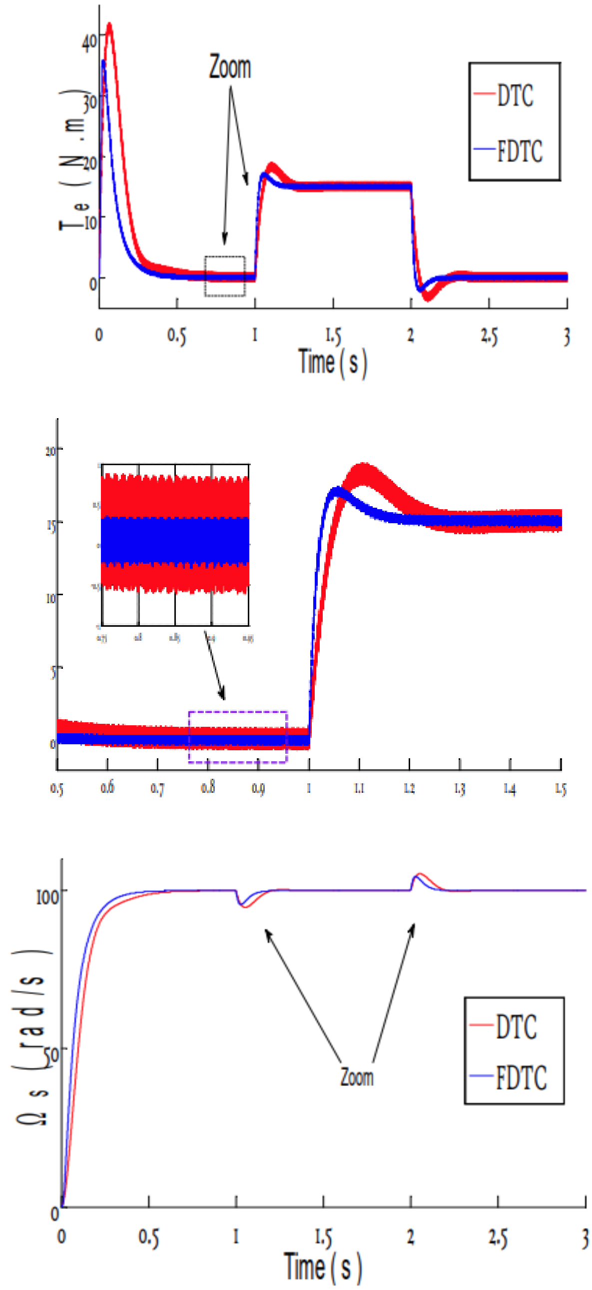
There are 36 rules that make up the control algorithm, and as an inference method, the max-min decision-based Mamdani method is used, because on the one hand it is easy to implement and on the other hand it gives better results. [5]

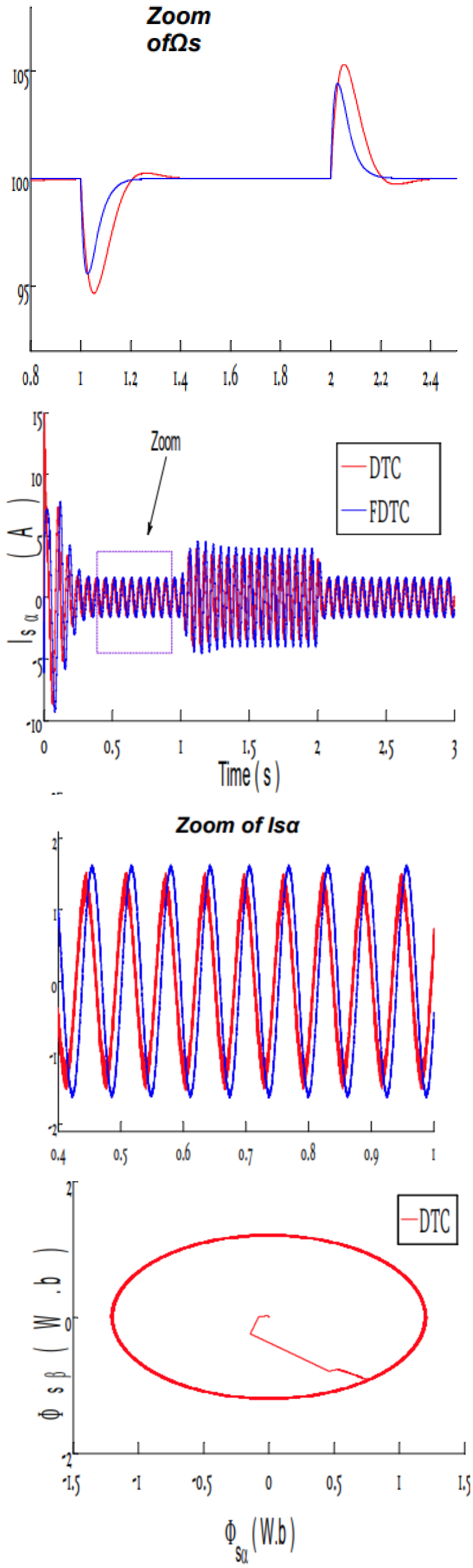
Simulation Results

To demonstrate the performance and robustness of DSIM fuzzy DTC control, the proposed scheme is implemented using Matlab/Simulink. Under variable operating conditions, the simulation work resulted in two robustness study tests: the first is the variation of the resistive torque; the second is the speed change and load torque variation.

Load torque variation

The figure. 10 presents the simulation results of a no-load start followed by an introduction of the load Cr = 15 N.m at time t = 1 s and its removal at time t = 2s, and the DSIM runs with a fixed speed 100 rad/s between instants: t=0s and t=3s.





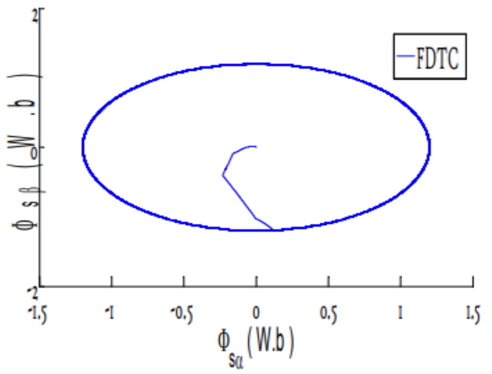


Fig. 10. Simulation results of load torque variation comparison between the FDTC and DTC.

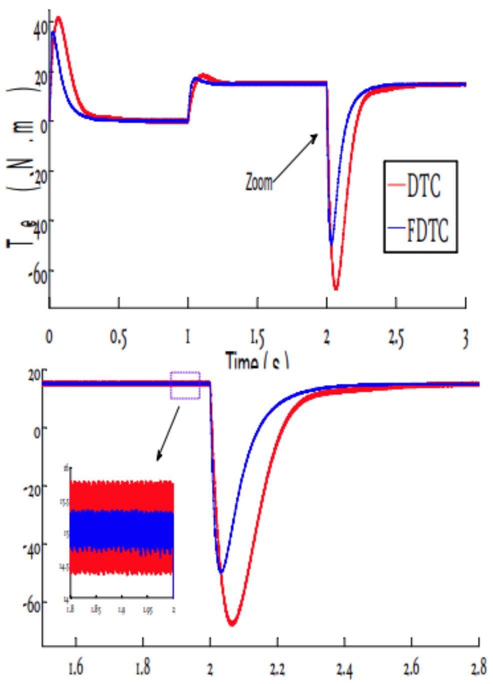
Figure 10, presents the comparisons between the FDTC based on the Fuzzy block on the one hand and the classic DTC on the other hand under the same sampling period, because the torque dynamics of FDTC is faster compared to conventional DTC.

Note that the torque ripple can be significantly reduced by using the DTC fuzzy method. In addition to this, it can also be seen that the speed reaches its target value without overshooting and the disturbing discharge due to load commands applied at different times as described above is practically the same for all commands.

The Star current responds well to fluctuations imposed by the electromagnetic pair, but maintains its sinusoidal shape and settles quickly during the transition phase, and the trajectory of the Star flux is practically circular for all controls.

Speed variation

To test the robustness of the control vis-à-vis the speed reference variations, we introduce in Figure 11, a speed reference change from 100 rad / s to 100 rad / s at time t = 2s after a load start 15 Nm at time t = 1s.



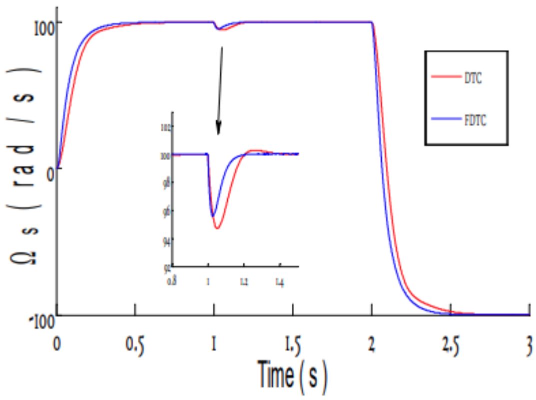


Fig. 11. Simulation results of Speed variation comparison between the FDTC and DTC.

Figure 11, shows that the speed and electromagnetic torque of the machine follow their reference values, the speed response time in FDTC control is very fast compared to the traditional DTC control, and the electromagnetic torque and flux performance of the machine in the case of FDTC produce less vibration. to traditional DTC control. Furthermore, it is clear that the effect of load torque does not affect the system speed response of either control technique.

Conclusion

In this work, we present the simulation of fuzzy DTC control of a double star induction motor (DSIM). Switching tables, sector blocks and hysteresis comparators for star flux and electromagnetic torque are replaced by smart technology. The obtained results confirm the effectiveness of the DSIM-based fuzzy DTC strategy for the control system. During testing, performance and robustness as well as torque, flux and current ripple have been reduced, speed follows reference values, there is no static error, and speed perturbation rejection is very fast. The flux has a better sinusoidal shape and a faster response to rotor speed. Future work will deal with the experimental implementation of the proposed method and will develop a hybrid model investigating different approaches to improve the control strategy.

appendix

Induction DISM parameters [20]:

$R_{s1,2}$= 3.72 (Ω)		R_r= 2.12(Ω)	
$L_{s1,2}$= 22 (mH)	L_r= 6 (mH)	L_m= 367.2(mH)	
K_f=0.001 (Nms/rad)		J= 0.006.25 (Nms^2/rad)	
P= 4500 (W)	220/380(V)	50(Hz)	p=1

REFERENCES

[1] Reghioui H., Belhamdi S., Ammar A., Lallouani H., Enhancement of Space Vector Modulation Based-Direct Torque Control Using Fuzzy PI Controller for Doubly Star Induction Motor. Advances in modeling and analysis C, Vol.74, No.2-4, pp.27-34, (2019).

[2] Hoanh K.D., Ren Y., Zhu Z.Q., Foster M., Modified switching-table strategy for reduction of current harmonics in direct torque controlled Doublethree- phase permanent magnet synchronous machine drives. IET Electric Power, 10-19 (2015).

[3] Listwan J., Pieńkowski K., DTC-ST and DTC-SVM Control of Five-Phase Induction Motor with MRAS[CC] estimator, Przegląd Elektrotechniczny, Vol.11, 2016, 252-256.

[4] Rahali, H.; Zeghlache, S.; Benalia, L.; Layadi, N.: Sliding mode control Based on Backstepping approach for a double star

induction motor (DSIM). Advances in modeling and analysis C, 150-157 (2018).
[5] El Ouanjil N., Motahhir S., Derouich A., El Ghzizal A., Chebabhi A., Taoussi M., Improved DTC strategy of doubly fed induction motor using fuzzy logic controller. Energy Reports 5, 271-279 (2019).
[6] Takahashi, I.; Noguchi, T.: Anew quick-response and high-efficiency control strategy of on induction motor. IEEE Transactions. On IA, 820-827 (1986).
[7] Depenbrock M., Direct Self-Control (DSC) of inverter-fed induction machine. IEEE Transactions. On Power Electronics, (1988).
[8] Ammar A., Kheldoun A., Metidji B., Amied T., Azzoug Y., Feedbak linearization based sensorless Direct Torque Control using Star flux MRAS-Sliding mode observer for induction motor drive. ISA Transactions, 382-392, (2020).
[9] Sadouni R., Meroufel A., Djriou S., Study and Simulation of Direct Torque Control (DTC) for a Six Phase Induction Machine (SPIM). International Journal of Energy, Issue 2, Vol. 7, 2013.
[10] Hamidreza H., Anton R., Vaimann T., Kallaste A., Taheri A., Holakooie, M.H.; Belahcen, A.: A novel vector control strategy for a six-phase induction motor with low torque ripples and harmonic currents. Energies, 1102 (2019).
[11] El Ouanjil N., Derouich A., El Ghzizal A., Motahhir S., Chebabhi A., El Mourabit Y., Taoussi M., Modern improvement techniques of dirct torque control for induction motor drives-a review. Protection and Control of Modern Power Systems, 11 (2019).
[12] Vignesh C., Sheela S.S., Devi E.C.M., Balachandar R., Direct Torque Control of Induction Motor Using Fuzzy Logic Controller. International Refereed Journal of Engineering and Science (IRJES), 56-61 (2014).
[13] Rajasekaran P., Senthilkumar V.J., Comparative Analysis of Two Level VSI and Three Level Neutral Point Clamped Inverter for Torque Ripple Reduction in Induction Drive. India Journal of Science and Technology, 1-7 (2016).
[14] Ammer A., Bourek A., Benakcha A, Robust load angle direct torque control with SVM for sensorless induction motor using sliding mode controller and observer. International Journal of Computer Aide Enginieering and Technology, 14-34, (2019).
[15] Johni J., Sukumaran R., Direct Torque Control Scheme for Induction Motor Using Fuzzy Logic Control. AIP Conference Proceedings, (2020).
[16] Ammer A., Improvement of Direct Torque Control Performances for Asynchronous Machine Using Non-Linear Techniques. Doctoral dissertation. Thesis, University MohmaedKhider, Biskra, Algeria, (2017).
[17] Chikh K., Khafallah M., Abdallah S., Improved DTC Algorithms for Reducing Torque and Flux Ripples of PMSM Based on Fuzzy Logic and PWM Techniques. MATLAB-A Fundamental Tool for Scientific Computing and Engineering Applications, (2012).
[18] Sudheer H., Kodad S.F., Sarvesh B.: Improved sensorless Direct Torque Control of induction motor using fuzzy logic and neural network based duty ratio controller. JAES International Journal of Artificial Intelligence(IJ-AI), 79-90 (2017).
[19] Rouabhi R., Abdessemed, R., Herizi A., Boudia M., Comparative Study Between Two Control Techniques Applied on the Permanent Magnet Synchronous Machine (PMSM). Advances in modeling and analysis C, 51-58 (2019).
[20] Lallouani H., Belhamdi S., Direct Torque Control of Doubly Star Induction Motor Using Fuzzy Logic Speed Controller. IAES International Journal of Artificial Intelligence(IJ-AI), 42-53 (2018).
[21] Lallouani H., Belhamdi S., Benyettou L., Reghioui H., Direct torque control of doubly star induction machine fed by voltage source inverter using type-2 fuzzy logic speed controller. Advances in modeling and analysis C, 202-207 (2018).
[22] Moat Y., Kouzi K, K., Investiating the Performances of Direct Torque and Flux Control for DoubleStar Induction Motor with Direct and Indirect Matrix Converter. PeriodicaPolytechnica Electrical Engineering and Computer Science, 97- 105 (2020).
[23] Layadi N., Zeghlache S., Berrabah F., Bentouhami L., Comparative Analysis between the Rotor Flux riented Control and Backstepping Control of a Double Star Induction Machine (DSIM) under Open-Phase Fault. AMSE Journals, Series Advances, 292-311 (2017).
[24] Azib A., Ziane D., Rekioua T., Tounzi A., Robustness of the Direct Torque Control of Double Star Induction Motor in Fault Condition. Rev. Rom. Sci. Techn-Electrotechn. Et Energ, 147-152 (2016).
[25] Ziane D., Azib A., Taib N., Rekioua T., Study and Design of the direct torque control of Double star induction motor. Journal of electrical systems, 114-124 (2013).
[26] El Ouanjil N., Taoussi M., Derouich A., Chebabhi A., El Ghzizal A., Boussoufi B., High Performance Direct Torque Control of Double fed Induction Motor using Fuzzy Logic. Gazi University journal of science, 532 – 542 (2018).
[27] Lisauskas S., Udris D., Uznys D., Direct Tourque Control of Induction Drive Using Fuzzy Controller. ElektronikairElektrotechnika, 13-16 (2013).
[28] Saber, K.; Gdaim, S.; Mtibaa, A.; Mimouni, M.F.: Design and Implementation of Direct Control Based on an Intelligent Technique of Induction Motor on FPGA. Journal of Electrical Engineering and Technology, 152-1539 (2015).
[29] Berrabeh F., Chebabhi A., Zeghlache S., Salah S., Direct Torque Control of Induction Motor fed by Three-Level Inverter Using Fuzzy Logic. AMSE Journals, Series Advances C, 248-265 (2017).
[30] Ganguly P., Kalam A., Zayegh A., Optimum Fuzzy Logic Control System Desing using Cuckoo Search Algorithm for Pitch Control of a Wind Turbine. Advances in modeling and analysis C, 266-280 (2017).