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DIRECT TORQUE CONTROL WITH SPACE VECTOR MODULATION USING INTERVAL TYPE 2 FUZZY LOGIC REGULATORS OF DUAL STAR INDUCTION MACHINE FED BY TWO THREE-LEVEL NEUTRAL POINT CLAMPED INVERTER

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Keywords: Dual star induction machine (DSIM); Three-level neutral point clamped inverter; Interval type-2 fuzzy logic regulator (IT2FLC); direct torque control with space vector modulation (DTC-SVM).

This paper introduces a direct torque control (DTC) method with space vector modulation (SVM) using interval type-2 fuzzy logic regulators for a dual-star induction machine fed by two three-level neutral point clamped inverters. The conventional DTC drive utilizes a pair of hysteresis comparators, which can lead to issues such as high torque ripple and variable switching frequency. As a result, we introduce several alternative methods, including DTC-SVM. We replace the hysteresis comparators with two Proportional-Integral (PI) regulators to enhance DTC performance, which generates the direct and quadrature voltage components in the d-q frame. The intricacy of the control system can make adjusting the PI regulator parameters difficult. To address this challenge, we propose using an interval type-2 fuzzy logic regulator for PI parameter adjustment in this paper. Our simulation results demonstrate the robustness and efficiency of the IT2FLC regulator.

1. INTRODUCTION

Over the past decade, electric drives for variable speed have become increasingly significant in industry and research. These drives demand a multidisciplinary approach in electrical engineering, including expertise in electrical machines, power electronics, computer science, programmable technologies, and dynamic systems control theory [1]. Multiphase machines, particularly dual-star induction machines, are commonly employed for speed variation or positioning. The former machines offer several benefits, including eliminating harmonics, reducing torque ripples and rotor losses, improving reliability, and segmenting power, resulting in high-power converter-machine assemblies [2]. Although the dual-star induction machine (DSIM) offers numerous advantages, its control can be challenging due to its nonlinear and strongly coupled basic model [3]. Another factor that adds to the complexity of the DSIM model is that the machine's parameters are only approximately known and may change over time. As a result, many control algorithms aim to enhance the DSIM's static and dynamic performance, achieving a decoupling of the flux and torque [4]. Within this context, the direct torque control was originally introduced in 1985 [5]. The direct torque control (DTC) approach provides a natural decoupling between the flux and torque, suppressing the pulse width modulation (PWM) to achieve excellent torque response. However, this strategy has significant drawbacks, such as the inability to determine the commutation frequency and strong torque oscillations [6]. The conventional regulation algorithm, such as the PI regulator, suffers from various drawbacks, including sensitivity to machine parametric uncertainties and their variations, long response time, and difficulty in rejecting large disturbances. To overcome these limitations, fuzzy control aims to address the classical process of controlling problems by leveraging behavioral knowledge that process specialists must formulate in linguistic (fuzzy) form. In practice, fuzzy systems that use fuzzy sets of type-1 represent magnitudes through membership values that range between 0 and 1 [8]. In the presence of uncertainties, defining premises and consequences becomes challenging. Type 2 fuzzy systems address this issue by incorporating uncertainties using fuzzy sets of type 2. In type 2 fuzzy sets, the membership values are themselves fuzzy sets of type 1 [9].

To overcome the limitations of traditional DTC and enhance its performance, numerous research studies are now focusing on utilizing contemporary control methods. These methods include DTC using a two-level inverter with SVM (DTC-SVM) and DTC using a three-level inverter with SVM (DTC-SVM-3N) [7]. [6] Has developed both a two-level SVM for induction machines and an SVM technique for three levels. The study by [8] investigates the implementation of DTC on a DSIM. Specifically, a DSIM powered by two 2-level inverters utilizes a single DTC-SVM system founded on IT2FLC regulators. Furthermore, [9] introduced a DTC-SVM approach that employs type 1 fuzzy logic. The main aim of this investigation is to explore direct torque control for a dual star induction machine with space vector modulation that utilizes interval type 2 fuzzy logic regulators, which are powered by two three-level neutral point clamped inverters. This type of inverter offers benefits, including sinusoidal output voltage waveforms, low total harmonic distortion of voltage and current, and a reduced switching frequency. Moreover, it has been demonstrated that DTC-SVM provides various benefits, such as a favorable dynamic response, consistent switching frequency, and sinusoidal line currents. Subsequently, employing an interval type 2 fuzzy regulator to mitigate the impact of these uncertainties will be explained and validated through quantitative error measures.

The organization of this article is as follows: section 2 and 3 provide the mathematical model of the DSIM and three-level inverter, respectively. In Section 4, the SVM model is described. The designed DTC models are

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introduced and elucidated in section 5, while section 6 outlines the establishment of IT2FLC to regulate the rotor speed, electromagnetic torque, and flux stator. Section 7 presents the simulation results and compares the performance of DTC-SVM-I2L-PI, DTC-SVM-I2L-T1FLC, and DTC-SVM-I3L-IT2FLC. Finally, section 8 concludes this paper.

2. **MODEL OF DSIM**

As depicted in Fig. 1, there are two stator windings, namely A_{s1}, B_{s1}, C_{s1} and A_{s2}, B_{s2}, C_{s2}, which are phase shifted by α = 30°. Additionally, there are three rotor phases A_r, B_r, and C_r, as reported in [1].

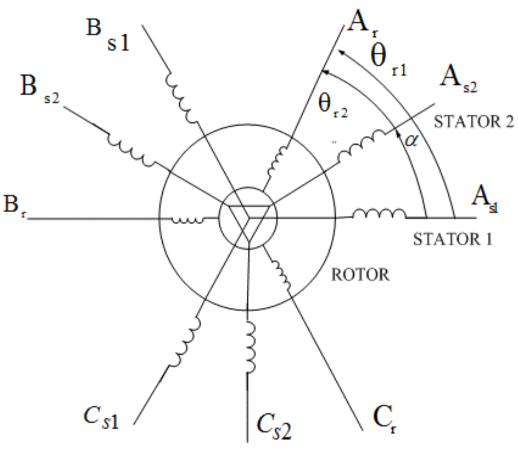


Fig. 1 – Dual star winding representation.

The dual star induction machine's voltage, flux, and torque equations are transformed into dimensional orthogonal subspaces, d-q, as described in [2].

(1) Voltage equation

$$\begin{cases} U_{S1d}=R_{S1}I_{S1d}+\frac{\mathrm{d}}{\mathrm{dt}}\phi_{S1d}-\omega_S\phi_{S1q} \\ U_{S1q}=R_{S1}I_{S1q}+\frac{\mathrm{d}}{\mathrm{dt}}\phi_{S1q}-\omega_S\phi_{S1d} \\ U_{S2d}=R_{S2}I_{S2d}+\frac{\mathrm{d}}{\mathrm{dt}}\phi_{S2d}-\omega_S\phi_{S2q} \\ U_{S2q}=R_{S2}I_{S2q}+\frac{\mathrm{d}}{\mathrm{dt}}\phi_{S2q}-\omega_S\phi_{S2d} \\ 0=R_rI_{rd}+\frac{d}{dt}\phi\emptyset_{rd}-(\omega_S-\omega_r)\phi_{rq} \\ 0=R_rI_{rq}+\frac{d}{dt}\phi_{rq}-(\omega_S-\omega_r)\phi_{rd} \end{cases}. \quad (1)$$

(2) Flux equation

$$\begin{cases} \phi_{S1d}=L_{S1}I_{S1d}+L_m(I_{S1d}+I_{S2d}+I_{rd}) \\ \phi_{S1q}=L_{S1}I_{S1q}+L_m(I_{S1q}+I_{S2q}+I_{rq}) \\ \phi_{S2d}=L_{S2}I_{S2d}+L_m(I_{S1d}+I_{S2d}+I_{rd}) \\ \phi_{S2q}=L_{S2}I_{S2q}+L_m(I_{S1q}+I_{S2q}+I_{rq}) \\ \phi_{S1d}=L_rI_{rd}+L_m(I_{S1d}+I_{S2d}+I_{rd}) \\ \phi_{S1q}=L_rI_{rq}+L_m(I_{S1q}+I_{S2q}+I_{rq}) \end{cases}. \quad (2)$$

(3) Electromagnetic torque equation

$$T_{em}=P(\phi_{S1d}I_{S1q}-\phi_{S1q}I_{S1d}+\phi_{S2d}I_{S2q}-\phi_{S2q}I_{S2d}), \quad (3)$$

(4) Mechanical equation

$$J\frac{\mathrm{d}\Omega}{\mathrm{dt}}=T_{em}-T_L+K_f\Omega. \quad (4)$$

3. **MODEL OF THREE-LEVEL INVERTER**

A three-level inverter (Fig. 2), feeds the stator windings of DSIM [11,12].

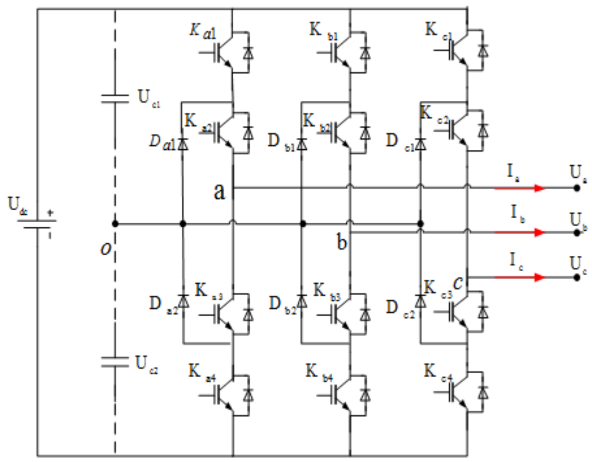


Fig. 2 – Schematic diagram of a three-level inverter.

The model for the three-level inverter is:

$$\begin{bmatrix} U_{an} \\ U_{bn} \\ U_{cn} \end{bmatrix}=\frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} U_{c1}F_a^2-U_{c2}F_a^0 \\ U_{c1}F_b^2-U_{c2}F_b^0 \\ U_{c1}F_c^2-U_{c2}F_c^0 \end{bmatrix} \quad (5)$$

where F_x^y is the switching function

4. **DTC-SVM**

The DTC command utilizes an SVM with a constant imposed frequency in this section. This approach generates a stator voltage reference, which is subsequently fed into an SVM block, as elaborated in [10]. The proposed method preserves the fundamental concept of the DTC approach and implements the stator flux orientation technique. The SVM technique and an interval type 2 fuzzy controller generate control voltages.

Furthermore, the estimation of the torque and flux is based on the DSIM's voltage model. This control structure offers the benefits of both field-oriented control (FOC) and direct torque control (DTC) and overcomes the limitations of conventional DTC. Leveraging interval type 2 fuzzy regulators and SVM achieves a fixed switching frequency, and the torque and flux pulsations are reduced.

4.1. STATOR FLUX CONTROL

The orientation of the stator flux in the reference frame (d, q) is depicted in Fig. 3. Specifically, the axis d aligns with the direction of the stator flux vector Φ_s. The magnitude of the stator current I_{sd} along the axis d is proportional to the amplitude of the stator flux. By regulating and maintaining a constant amplitude of the I_{sd} component, decoupling between the control of the machine's torque and flux can be achieved, as outlined in [8,14].

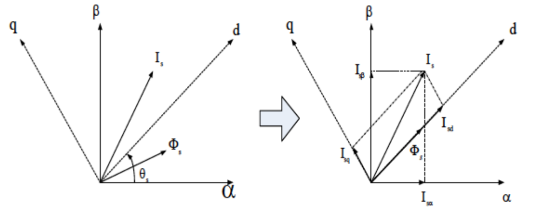


Fig. 3 – Vector representation of the stator flux orientation strategy.

From the developed model of the DSIM, we deduce an expression of the stator flux vector. So, if the stator flux is oriented on the axis of one to therefore [6]:

$$\phi_{Skd} = \phi_{Skd}, \qquad \phi_{Skq} = 0$$

$$\begin{cases} \phi_{Sk} = ((1+\sigma T_r s) I_{Skd} + \sigma T_r(\omega_S - \omega_r) I_{Skq} + \left(\frac{L_{Sk}+2L_m}{1+\sigma T_r s}\right) \\ I_{Skd} = -\left(\frac{1}{L_{Sk}+2L_m}\phi_{Sk} - \sigma I_{Skd}\right)\left(\frac{T_r(\omega_S-\omega_r)}{1+\sigma T_r s}\right) \end{cases} \quad (6)$$

The stator voltages can be expressed as follows by representing the d-component of the stator current as a function of the q-component and the stator flux:

$$\begin{cases} U_{Skd} = \dfrac{\phi_{Sk}}{G_{\phi_{Sk}}} + E_d \\ U_{Skq} \approx \omega_S \phi_{Sk} \end{cases}. \quad (7)$$

with

$$\begin{cases} G_{\phi_{Sk}} = \dfrac{T_{Sk}(1+\sigma T_r s)}{1+(T_{Sk}+T_r)s + \sigma T_{Sk} T_r s^2} \\ E_d = -\dfrac{\sigma R_{Sk} T_r}{1+\sigma T_r s} I_{Skq}(\omega_S - \omega_r) \end{cases}. \quad (8)$$

Controlling the d component of the stator voltage allows for regulation of the stator flux.

4.2. ELECTROMAGNETIC TORQUE CONTROL

The vector module ϕ_{Sk} remains constant and equal to its reference value ϕ^*_{SK}, and $\sigma T_r \ll 1$; the relation (7) can be simplified under the following formula [8]:

$$T_{em} = 2p\frac{T_r(1-\sigma)}{L_{Sk}+2L_m}\frac{\phi^2_{SK}(\omega_S-\omega_r)}{(1+2\sigma T_r s)}. \quad (9)$$

Equation (9) can be expressed as follows, given that the electromagnetic torque is proportional to the slip pulse:

$$T_{em} = G_{T_{em}}(\omega_S - \omega_r), \quad (10)$$

where

$$G_{T_{em}} = 2p\frac{T_r(1-\sigma)}{L_{Sk}+2L_m}\frac{\phi^2_{SK}}{(1+2\sigma T_r s)}. \quad (11)$$

The torque can be controlled by the stator pulsation.

4.3. SPACE VECTOR MODULATION (SVM)

The SVM operates by projecting the desired reference voltage vector $\vec{U}^*$, onto the two axes of the (α, β) torque plane [8]. Calculating the desired switching times requires determining the values of these projections, which correspond to two non-zero switching states of the inverter. The combined value of the two switching times must be less than the inverter's switching period [15]. To maintain a constant frequency-switching rate, the inverter is held in a zero state for a complementary duration to T_h [16].

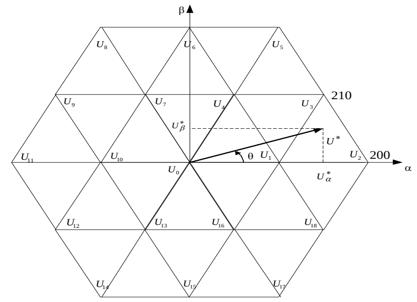


Fig. 4 – Diagram of SVM with 3-level inverter.

Figure 5 depicts the four triangles of the first sector and the corresponding straight lines (Δ1), (Δ2), and (Δ3) that form their boundaries.

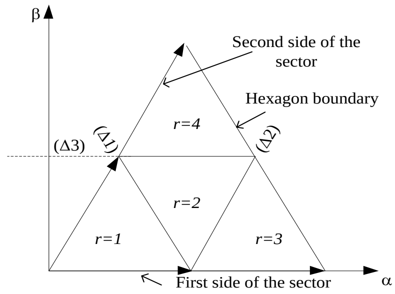


Fig. 5 – Division of first sector to 4 triangles.

The Cartesian equations of the straight lines U_β as a function of U_α is given by:

$$\begin{cases} (\Delta 1) \quad U_\beta = -\sqrt{3}\,U_\alpha + \sqrt{1/2}\;U_{dc} \\ (\Delta 2) \quad U_\beta = \sqrt{3}\,U_\alpha - \sqrt{1/2}\;U_{dc} \\ (\Delta 3) \quad U_\beta = \sqrt{1/8}\;U_{dc} \end{cases}. \quad (12)$$

The switching times t_q, t_p and t_u according to the amplitude of the reference vector as follows:

$$\begin{bmatrix} t_p \\ t_q \\ t_u \end{bmatrix} = T_h \begin{bmatrix} U^*_\alpha \\ U^*_\beta \\ 1 \end{bmatrix} \begin{bmatrix} U_{\alpha p} & U_{\alpha q} & U_{\alpha u} \\ U_{\beta p} & U_{\beta q} & U_{\beta u} \\ 1 & 1 & 1 \end{bmatrix}^{-1}. \quad (13)$$

By performing the same calculation for each sector and then determining the corresponding pulse widths (duration of the switch closures) according to Fig. 6.

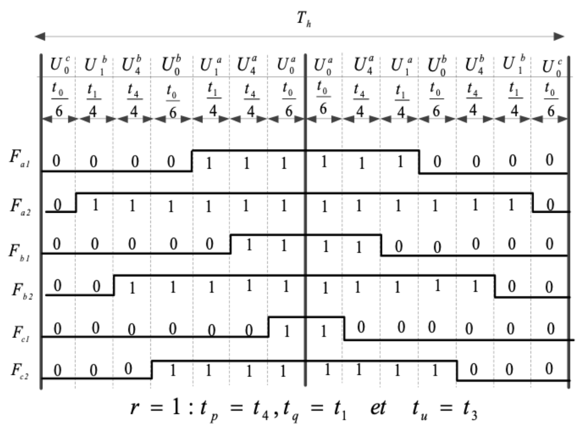


Fig. 6 – Leg voltages and space vector disposition in sector I.

4.4. DESIGN OF INTERVAL TYPE-2 FUZZY LOGIC CONTROLLER

Zadeh [17] introduced a fuzzy type 2 system to extend the fuzzy set type 1. A fuzzy set type 2 is defined by a fuzzy membership function where the degree of membership for each element is represented as a fuzzy set within the range [0,1]. This type of set is useful in cases where there is uncertainty in the membership value, either in the form of the membership function or one of its parameters. A traditional fuzzy controller comprises a fuzzification interface, a rule base, an inference system, and a defuzzification interface. Similarly, the interval type 2 fuzzy controller has a comparable structure but uses a type of reducer to convert type 2 fuzzy sets into type 1 ones before the defuzzification phase. The diagram below [8,17,18] illustrates the various operations involved:

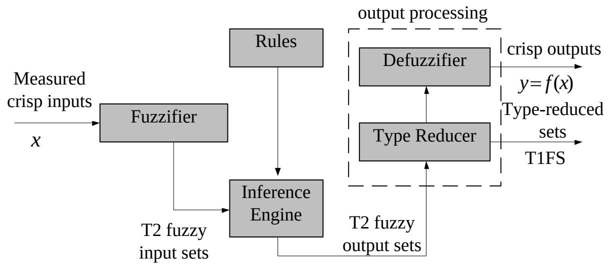


Fig. 7 – Structure of IT2FLS [16].

1) Fuzzification. Using their membership functions, calculate the membership degrees of $e(k)$ and $e(k)$ for the different classes.
2) Inference engine. Calculate the membership functions resulting from each class's linguistic variable $u(k)$.
3) Defuzzification. Transforms linguistic output of type reduction to a physically applicable numeric variable.
4) Type reducer.

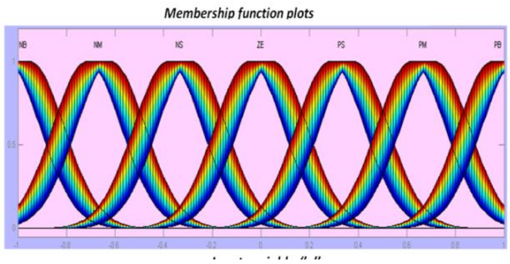


Fig. 8 – Membership functions of error speed and variation.

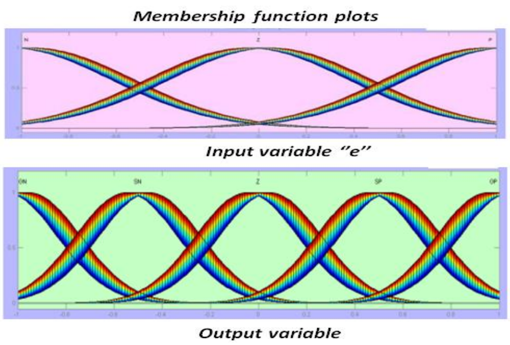


Fig. 9 – Membership functions of error torque and error flux and variation.

The centroid method is utilized to convert a type 2 fuzzy set to a type 1 fuzzy set.

The inputs of the IT2FLC are the error and its variation:

$$\begin{cases} e(k)=X_{ref}(K)-X_r(K) \\ \Delta e(k)=e(k)-e(k-1) \end{cases}. \qquad (14)$$

and X (speed rotor, electromagnetic torque, and stator flux).

In our work, the fuzzy controller admits fuzzy sets of Gaussian form for the error and variation of the error and singletons for the control variable (speed, torque, and flux) represented in Figs. 8, 9. Tables 1 and 2 give the fuzzy rules table.

Table 1

Rule base of speed IT2FLC

u		e						
		NB	NM	NS	EZ	PS	PM	PB
de	NB	NB	NB	NB	NB	NM	NS	EZ
	NM	NB	NB	NB	NM	NS	EZ	PS
	NS	NB	NB	NM	NS	EZ	PS	PM
	EZ	NB	NM	NS	EZ	PS	PM	PB
	PS	NM	NS	EZ	PS	PM	PB	PB
	PM	NS	EZ	PS	PM	PB	PB	PB
	PB	EZ	PS	PM	PB	PB	PB	PB

Table 2

Rule base of flux and torque IT2FLC

u		e		
		N	Z	P
de	N	NB	NS	PS
	Z	NB	Z	PB
	P	NS	PS	PB

In this table, NB, NM, NS, EZ, PS, PM, and PB represent negative, positive, zero, small, medium, and big, respectively. For example, NB means negative big.

5. **RESULTS AND DISCUSSION**

The simulation was performed using MATLAB/Simulink, and the results are presented below. The appendix contains a summary of the DSIM parameters.

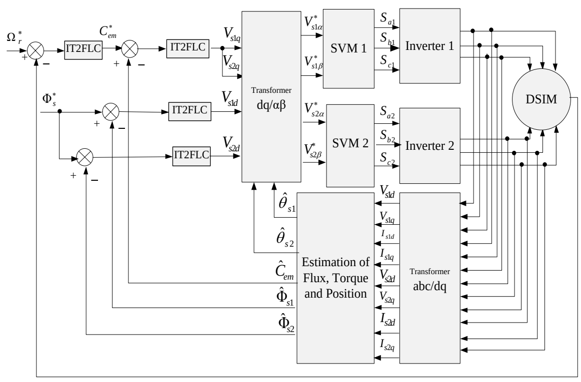
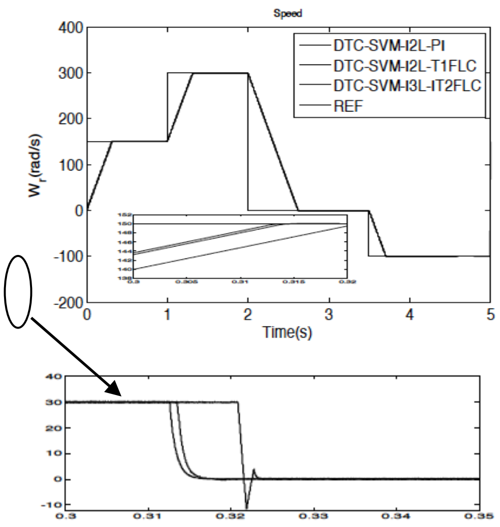


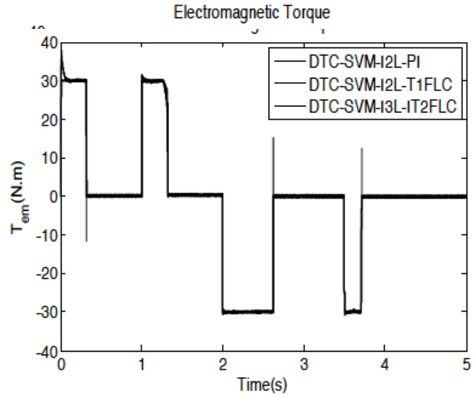
Fig. 10 – DTC-SVM-I3L based on IT2FLC of DSIM.

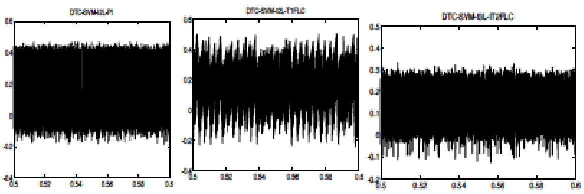
Figure 11 shows the technical differences in the commands applied. The test of concern simulates a no-load DSIM start-up, with the reference speed set at 150 rad/s. At t = 1 s, the speed is increased to 300 rad/s, and at time 2 s, the direction of rotation of the DSIM is reversed by 0 rad/s and by 100 rad/s at t = 3.5 s.

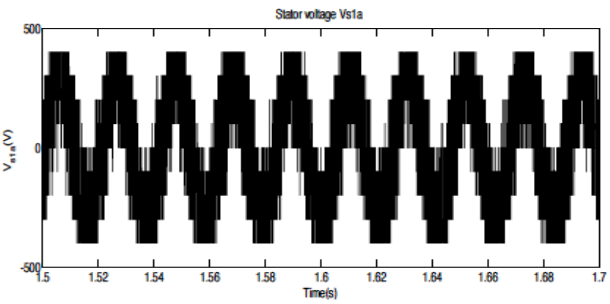
We noted that the ripple at the torque is very low because of the absence of hysteresis regulators. Thus, the torque has a very narrow form compared to the results of (DTC-SVM-I2L-PI and DTC-SVM-I2L-T1FLC). It reaches its reference speed (150, 300, 0, 100 rad/s).

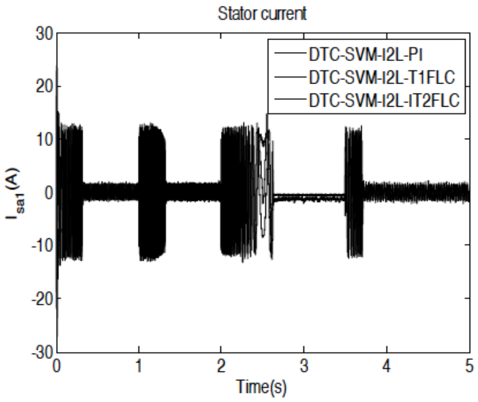
Three common performance criteria, namely the integral of the squared error (ISE), the integral of the absolute value of the error (IAE), and the integral of time multiplied by the absolute value of the error (ITAE) [8], are employed to measure the errors.











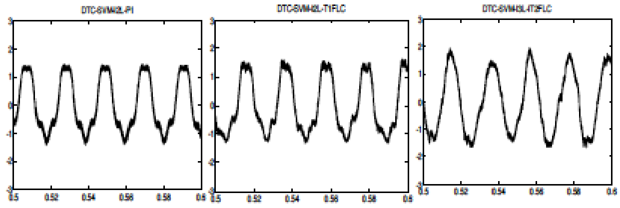


Fig. 11 – DTC-SVM-IT2FLC multilevel DSIM simulation result with the speed variation.

Table 3

Quantitative comparison

		DTC-SVM - two level inverter-PI	DTC-SVM- two level inverter- T1FLC.	DTC-SVM- three level inverter- IT2FLC
Torque Ripple		0,5	0,45	0,3
THD (%)		19,19	11,91	4,99
Speed	ISE	$2{,}419{*}10^4$	$2{,}414{*}10^4$	$2{,}405{*}10^4$
	IAE	152,1	151,4	150,9
	ITAE	272,8	272	271,8
Torque	ISE	1885	1882	1304
	IAE	72,24	72,23	44,36
	ITAE	191,9	191,2	79,65

This comparison shows that the DTC-SVM-I3L-IT2FLC performs well and is more robust than DTC-SVM-I2L-PI and DTC-SVM-I2L-T1FLC.

6. **CONCLUSION**

The current paper presents the DTC-SVM control of a dual-star induction machine powered by two three-level voltage inverters. The control scheme utilizes robust tuning algorithms based on interval type 2 fuzzy logic to regulate the DSIM's speed, electromagnetic torque, and stator flux.

In the first part, the modeling of the DSIM based on the equivalent model of Park and three-level inverters considering the simplifying assumptions was studied.

Efficient control of the DSIM requires decoupling between the electrical component (flux) and the mechanical component (torque). For this, direct torque control (DTC) has been introduced as a control technique that makes asynchronous machine control possible, like a separate excitation dc machine whose decoupling between the flux and the torque is natural.

Simulation results showed the superiority of interval type 2 fuzzy regulators over conventional PI and type 1 fuzzy regulators, and DTC-SVM-I3L using the interval type 2 fuzzy controllers gives better performances compared to DTC-SVM-I2L-T1FLC and DTC-SVM-I2L-PI (considerable reduction of the ripples of the torque and the flux).

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REFERENCES

1. R. Anagha, M. Soman, M. Holmukhe, *Double stator induction machine for variable speed and variable torque applications*, SSRG International Journal of Electrical and Electronics Engineering, **8**, *12*, (2021).
2. R. Belal, M. Flitti, M.L. Zegai, *Tunning of PI speed controller in direct torque control of dual star induction motor based on genetic algorithms and neuro-fuzzy schemes*, Rev. Roum. Sci. Techn. – Electrotechn. et Energ. **69**, *1*, pp. 9–14 (2024).
3. M.I. Abdelwanis, A.A. Zaky, *Maximum power point tracking in a perovskite solar pumping system with a six-phase induction motor* Rev. Roum. Sci. Techn. – Electrotechn. et Energ. **69**, *1*, pp. 15–20 (2024).

4. M. Hojat, A.S- Mohammad, *Controlling the speed and flux of a dual stator winding induction motor using anemotional intelligent controller and integration algorithm*, Turk. J. Elec. Eng.&Comp. Sci., **26**, pp. 3192–3206. (2018).
5. L. Hellali, S. Belhamdi, *Performances of type 2 fuzzy logic control based on direct torque control for double star induction machine*. Rev. Roum. Sci. Techn. – Electrotechn. et Energ., **65**, *1–2*, pp. 103–108 (2020).
6. Ehsan Hassankhan, and Davood A. Khaburi, *DTC-SVM scheme for induction motors fed with a three-level inverter*, World Academy of Science, Engineering and Technology, **44**, pp. 168–172 (2008)
7. B. Abdelmalik, S. Saad, A. Abdelhak, L. Yahia, *A study of SVM-DTC and conventional DTC for induction motors drive fed by five-level inverter*, European Journal of Electrical Engineering, **21**, *1*, pp. 85–96 (2019).
8. L. Hellali, S. Belhamdi, L. Benyettou. *DTC-SVM based on interval type-2 fuzzy logic controller of double stator induction machine fed by six-phase inverter*, International Journal of Image, Graphics and Signal Processing (IJIGSP), **11**, *7*, pp. 48–57 (2019).
9. H. Reghioui, S. Belhamdi, A. Abdelkarim, *Enhancement of space vector modulation based-direct torque control using Fuzzy PIController for doubly star induction*, Motor Advances in Modelling and Analysis C. **74**, *2–4*, pp. 63–74 (2019).
10. A. Meroufel, S. Massoum, A. Bentaallah, P. Wira, F. Belaimeche, A. Massoum, *Double star induction motor direct torque control with fuzzy sliding mode speed controller*, Rev. Roum. Sci. Techn. – Electrotechn. et Energ., **1**, pp. 31–35 (2017).
11. D. Lalili, E. M.Berkouk, F.Boudjema, N. Lourci, T.Taleb, J. Petzold. *Simplified space vector PWM algorithm for three-level inverter with neutral point potential control*, The Mediterranean Journal of Measurement and Control, **3**, *1*, pp. 30–39 (2007).
12. E. Benyoussef, A. Meroufel, S. Barkat, *Three-level direct torque control based on artificial neural network of double star synchronous machine*, Leonardo Journal of Sciences, **13**, *24*, pp. 15–27 (2014).
13. R. Sadouni, *Three-level DTC SVM for dual star induction motor fed by TowCascade VSI with DPCVF SVM*, Rectifier Journal of Power Technologies, **100**, *2*, pp. 171–177 (2020)
14. F. Berrabah, S. Salah, A. Chebabhi, *SVM technique based on DTC sensorless control optimized by ANN applied to a double stator asynchronous machine fed by three level six-phase inverter*, The Mediterranean Journal of Measurement and Control, **12**, *2*, pp. 571–579 (2016).
15. E. Monmasson, J.P. Louis *Presentation of a control law for IM drive based on the dynamic reconfiguration of a DTC algorithm and a SVM-DTC algorithm*, Electric Power systems Research, **63**, pp. 321–333 (2003).
16. T.G. Motorola, F. Habetler, F. Profumo, M.Pastorelli, L. Tolbert. *Direct torque control of induction machines using space vector modulation*, IEEE Transaction on Industry Applications, **28**, *5*, pp. 1045–1053 (1992)
17. J.M. Mendel. *Advances in type-2 fuzzy sets and systems*, Information Sciences, **177**, pp. 84-110 (2007)
18. I. Hamdan, M.M.M. Youssef, O. Noureldeen, *Influence of interval type-2 fuzzy control approach for a grid-interconnected doubly - fed induction generator driven by wind energy turbines in variable-speed system*, SN Appl. Sci., **5**, *25* (2023).

APPENDIX

DSIM PARAMETERS [8]

Stators1,2 resistances	3.72 Ω
Rotor resistance	2.12 Ω
Stators1,2self inductances	0.022H
Rotor inductance	0.006H
Mutual inductance	0.3672H
Moment of inertia	0.0625Nms2/rad
Friction coefficient	0.001Nms/rad

GREEK SYMBOLS

Ω_r	The rotor angular speed
θ_s	Angle between stator and rotor flux

SUBSCRIPTS

P	Number of pole pairs
J	Moment of inertia
K_f	Friction coefficient
f	Frequency
T_L	Load torque
U_{an}, U_{an}, U_{an}, U_{an}, U_{an},	Direct voltage source