# MODELING AND SIMULATION OF DUAL STAR INDUCTION MOTOR CONTROL USING DTC AND DIRECT FIELD ORIENTED CONTROL: A COMPARATIVE STUDY

**BRAHIM KIYYOUR, DJEMAI NAIMI [1] and AHMED SALHI [1]**

(1) Laboratory of electrical engineering Biskra, "LGEB", *University of Biskra, Algeria*

bkiyyour@yahoo.fr, naimi.djemai@gmail.com

## ABSTRACT

This paper presents a comparative study on two control strategies for dual star asynchronous induction motor (DSIM) drives , the first uses a direct field-oriented control (DFOC) based on rotor flux orientation, or the machine is supplied by two voltage source inverters based on sinus-triangular pulse-width modulation techniques, the second employs¶ direct torque control (DTC), this technique uses the instantaneous values of voltage vector where each reference voltage vector is computed with a DTC algorithm. The performances of the two control schemes are evaluated in terms of torque and current ripples, and transient responses to load torque variation. We can nevertheless say that the two control schemes provide in their basic configuration, comparable performances regarding the torque control and parameter sensitivity. We can note a slight advance of DTC scheme compared to DFOC scheme regarding the dynamic flux control performance and the implementation complexity. The choice of one or the other scheme will depend mainly on specific requirements of the application. The results obtained by simulation are presented and discussed.

**KEYWORDS:** Dual star induction motor (DSIM), direct field-oriented control (DFOC), direct torque control (DTC), comparative study.

## RESUME

Cet article présente une étude comparative entre deux stratégies de commande appliqués à une machine asynchrone double étoile (MASDE), la première est la commande directe par orientation de flux rotorique (DFOC) , où la machine est alimentée par deux onduleurs de tension à MLI, la seconde est la commande direct du couple (DTC), cette technique utilise les valeurs instantanées du vecteur de tension où chaque vecteur de tension de référence est calculé avec un algorithme DTC. Les performances des deux schémas de commande sont évaluées en termes d'ondulations de couple et de courant et les réponses transitoires à la variation du couple de charge. On peut néanmoins dire que les deux systèmes de contrôle fournissent dans leur configuration de base, des performances comparables concernant le contrôle du couple et la sensibilité des paramètres. Nous pouvons constater une légère avancée du système DTC par rapport au DFOC en ce qui concerne la performance du contrôle du flux dynamique et la complexité de l'implémentation. Le choix de l'un ou l'autre technique dépendra principalement a des exigences de l'application. Les résultats obtenus par simulation sont présentés et discutés.

**MOTS CLES:** Machine asynchrone double étoile (MASDE), commande directe par orientation de flux rotorique (DFOC), commande direct du couple (DTC), étude comparative.

## 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. Switching of the converter switches must take place at high current and at higher switching frequencies, which requires the use of high-gauge components. On the other hand, the winding of the machines must be dimensioned in such a way that Support a high voltage [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 powered by one or more converter, For this the multi-phase machines are increasingly present in industrial applications of high power 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].

Direct Field Oriented Control (DFOC) and Direct Torque Control (DTC) allow torque and flux to be decoupled and controlled independently to achieve a dynamic performance at least equivalent to that of a commutator and DC motor. These control strategies are different on the operation principle but their objectives are the same. They aim both to control effectively the motor torque and flux in order to force the motor to accurately track the command trajectory regardless of the machine and load parameter variation or any extraneous disturbances. Both control strategies have been successfully implemented in industrial products.

With the direct field orientation control (DFOC) method, dual star induction machine drives are becoming a major candidate in high-performance motion control applications, where servo quality operation is required. Fast transient response is made possible by decoupled torque and flux control.

The DTC method was proposed by I.Takahashi [5]. It is based on the errors between the reference and the estimated values of torque and flux for to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits. To this end, it uses tables to select the switching procedure based on the inverter states and reduces the influence of the parameter variation during the operation [6].

This paper focuses on detail comparison between two common control methods including direct Field Oriented Control (DFOC) and Direct Torque Control (DTC) of the dual star induction motor. The main characteristics of the motor such as torque, flux and speed under different operation conditions studied and the advantages of DFOC and DTC are obtained.

## 2 MATHEMATICAL MODEL OF DUAL STAR INDUCTION MOTOR

In the mathematical description of dual stator induction motor it is assumed that the DSIM motor is considered as an electromechanical system consisting of two three-phase stator windings, denoted as stator 1 and stator 2, whose magnetic axes are displaced by α =30° electrical angle. and the common squirrel-cage rotor winding. The cage rotor winding is replaced by an equivalent three-phase winding[2,7]. Figure 01 shows the representation of the stator and rotor windings of dual stator induction motor.

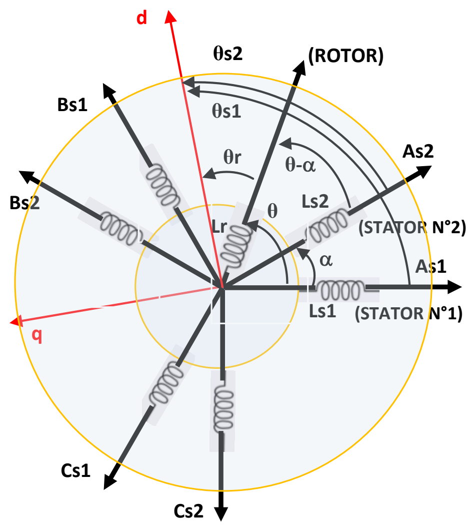



*Figure 01: Windings scheme of DSIM*

General voltage equations for stator and rotor circuits for Model of the DSIM motor have the following matrix form:

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

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

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

In the synchronous d-q reference frame rotating at ωs speed, the model of the DSIM is given by the following equations[8,10]:

### STATORS VOLTAGE COMPONENTS:

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

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

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

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

### ROTOR VOLTAGE COMPONENTS

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

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

**STATOR FLUX COMPONENTS**

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

$$\phi_{qs1} = L_{s1}\, i_{qs1} + L_m\, (i_{qs1} + i_{qs2} + i_{qr}) \quad (4)$$

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

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

**ROTOR FLUX COMPONENTS**

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

$$\phi_{qr} = L_r\, i_{qr} + L_m\, (i_{qs1} + i_{qs2} + i_{qr}) \quad (5)$$

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

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.

**DSIM ELECTROMAGNETIC TORQUE**

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:

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

Where: p is the number of poles pairs

Mechanical equation:

$$J\frac{d\Omega}{dt} = T_e - T_r - k_f \Omega$$

## 3 DESCRIPTION OF FIELD-ORIENTED CONTROL AND DIRECT TORQUE CONTROLS SCHEMES

### 3.1 Field-Oriented Control System

The main goal of a direct field-oriented control (DFOC) is to obtain decoupled control of electromagnetic torque and rotor flux of the motor [9]. It is considered the DFOC control system of DSIM with application of the rotor flux vector orientation. The algorithm of DFOC control is based on the mathematical equations of DSIM formulated in the common reference frame (d, q) with the d-axis aligned with the vector of rotor flux linkage see figure 02.

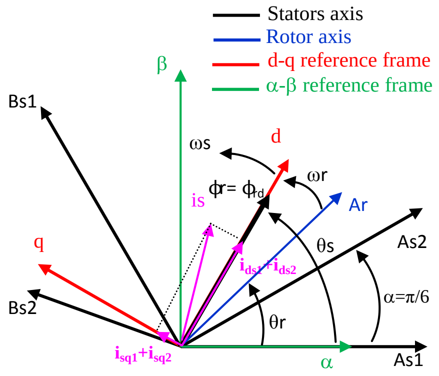



***Figure 02: Space vector diagram of DFOC control***

$$\phi_{dr} = \phi_r$$

$$\phi_{qr} = 0$$

Figure 03 shows a block diagram of the direct field oriented control system for dual star induction motor

By applying this principle ($\phi_{dr} = \phi_r$ and $\phi_{qr} = 0$) to equations (2), (3), (4) and (5), the finals expressions of the electromagnetic torque and slip speed are:

$$\omega_{sl} = (\omega_s - \omega_r) = \frac{R_r L_m}{L_m + L_r} \frac{(i_{qs1} + i_{qs2})}{\phi_r} \quad (6)$$

$$T_e = P\frac{L_m}{L_m + L_r}\left[(i_{qs1} + i_{qs2})\phi_r\right]$$

where: $\omega_{sl}$ rotor slip speed,

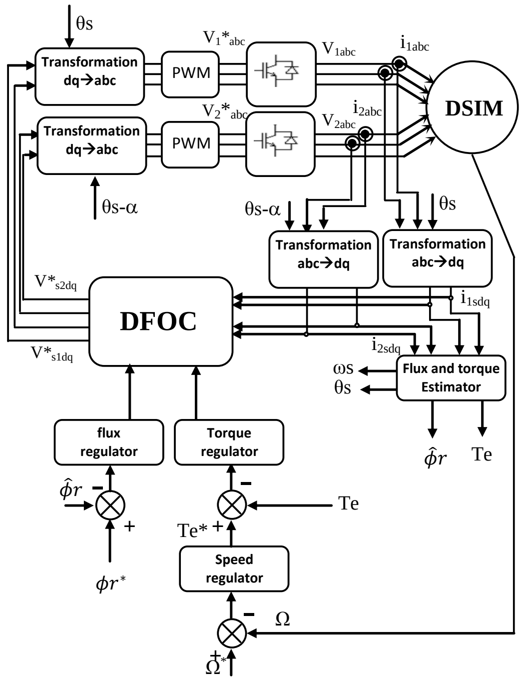



***Figure 03: direct field oriented control scheme for DSIM***

The current controller has been implemented in the rotor flux reference frame using PI regulators with back emf compensation.

Note that, the application of conventional DFOC approach to different types of special electric machines is reported in the literature [10].

### 3.2 Direct torque control (DTC) of dual stator induction motor

The basic DTC scheme is shown in Figure 04. DTC method is based on instantaneous space vector theory. By optimal selection of the space voltage vectors in each sampling period, 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. 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 can also be explained by analyzing the stator voltage equation in the stator flux reference frame [13].

For effective control of the torque of DSIM it is imperative to properly adjust the flux. To do this we place ourselves in a fixed frame (α, β) related to the stator of the machine. .[8] [12]

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

$$\phi_{s\alpha1,2} = \int_0^t \left(V_{s\alpha1,2} - R_{s1,2}\, i_{s\alpha,1,2}\right)dt$$
$$\phi_{s\beta1,2} = \int_0^t \left(V_{s\beta1,2} - R_{s1,2}\, i_{s\beta,1,2}\right)dt \qquad (7)$$

Thus, the stator flux module is written:

$$\phi_s = \sqrt{(\phi_{s\alpha1} - \phi_{s\alpha2})^2 + (\phi_{s\beta1} - \phi_{s\beta2})^2} \qquad (8)$$

The angle θs shift vector ∅s is given by the following expression:

$$\theta_s = Arctg\left(\frac{\phi_{s\alpha1} + \phi_{s\alpha2}}{\phi_{s\beta1} + \phi_{s\beta2}}\right)$$

The calculation of the stator flux is not sufficient to control the torque of the machine. An estimate of the torque in real time is required. For this, an expression of the torque was included in the program.

$$T_e = P.\left(\phi_{s\alpha1} \cdot i_{s\beta1} + \phi_{s\alpha2} \cdot \phi_{s\beta2} - \phi_{s\beta1} \cdot i_{s\alpha1} + \phi_{s\beta2} \cdot i_{s\alpha2}\right)$$

The error between the estimated torque and the reference torque is the input of a three level hysteresis comparator

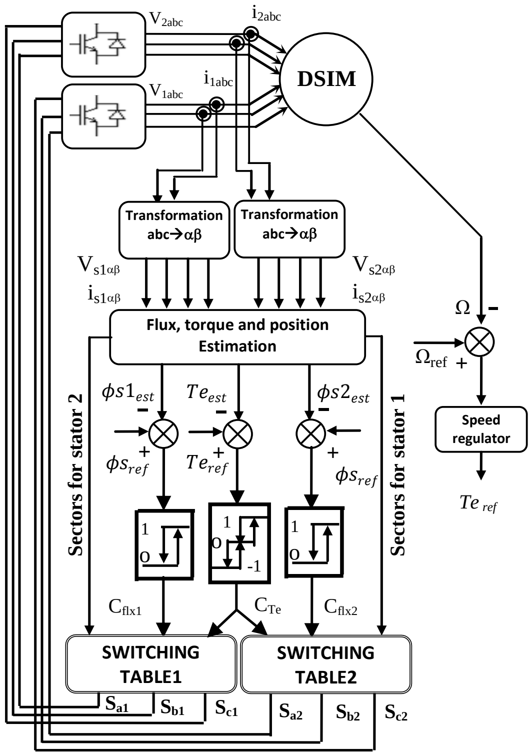



*Figure 04: direct torque control (DTC) scheme for DSIM*

The goal of DTC of dual star induction motor is to maintain the stator flux and torque within the limits of flux and torque hysteresis bands by proper selection of the stator space voltage vectors during each sampling period figure 05. 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 the stator flux and torque, assuming the stator flux is located in the first sector.

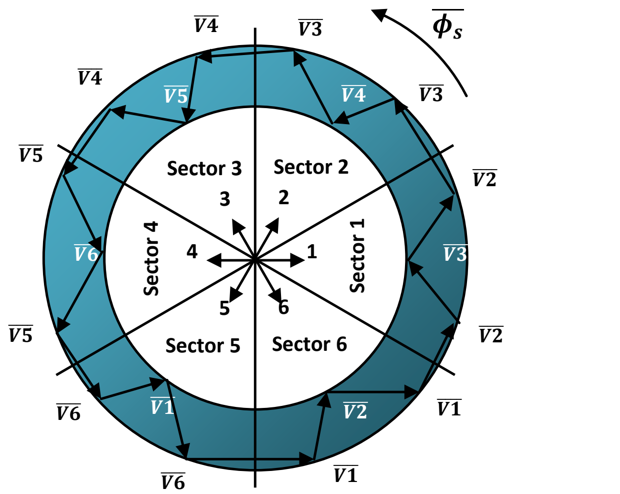



*Figure 05: Rotation of stator flux linkage vector by voltage vector*

*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 |

In this section, static and dynamic performances of DFOC and DTC schemes are obtained by simulation using the MATLAB/ Simulink Power System Blockset. Since the objective of the work is to compare the control strategies, the same power section is used in both systems. It is necessary to make a comparison of static and dynamic characteristics of both technical command and under the same operating conditions (reference, charges disturbance… etc.), and in the same configuration simulation (step sampling, time simulation,) In this paper we will present the advantages and disadvantages of each type of command, better command will be the one that best meets the requirement to know:

- Best performance static and dynamic.
- Best prosecution guidelines control.

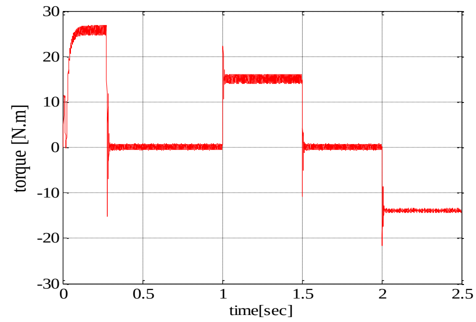
## 4 SIMULATION RESULTS

A detailed comparison between the two techniques has been carried out by numerical simulations using

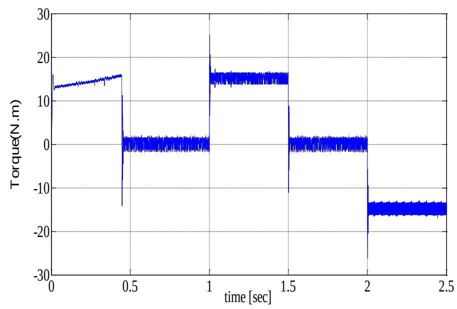
matlab/simulink. Output specifications of two control system should be compared with each other in the same operational conditions.

Figure (6,7) show machine torque variations in terms of time for two control methods. The performance of the two schemes has been compared by analyzing the response to a step variation of the load torque of +15 Nm (nominal torque) during a period of t = [1 2] s and for -15 Nm between t = 2s to T = 2.5 s after a leadless starting, for two control the actual torque follows reference torque very fast when reference torque changes. At first starting torque increases, after arriving a specified speed, torque profile will have stable swings around a zero. The torque ripples is between 16.54 to 13.72 and for DTC while is between 15.92 and 14.22,

Based on achieved results, we can conclude that DTC based on hysteresis comparators and switching tables provides a fast torque response. However, in steady state the torque has large ripples due to the switching frequency of the inverter caused by the hysteresis bands.




*(a) DFOC*




*(b) DTC*

*Figure 06: torque response (a) DFOC scheme, (b) DTC scheme*

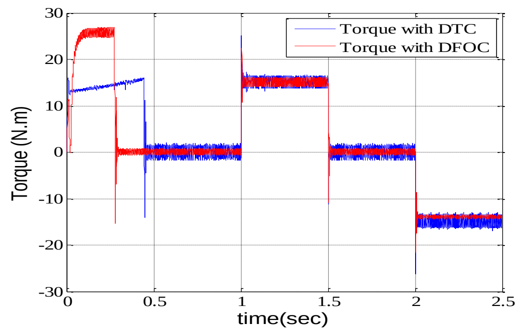
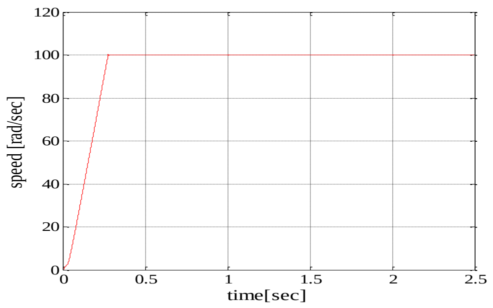


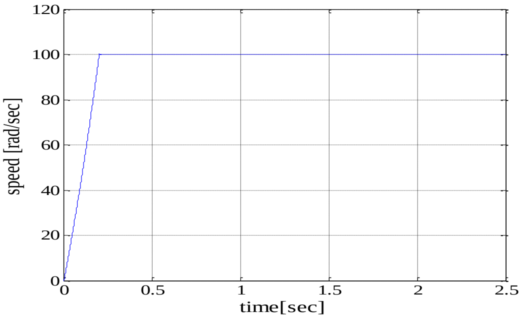

*Figure 07: Comparison at the variation torque load*

Simulated waveforms of rotor speed and stator current, shown in Figure 8 and 9 successive. The reference speed was 100 rad/sec. The actual speed of the rotor settled to its reference speed in 0.22 seconds for DTC and 0.287 seconds for DFOC, It is observed from that during load changes the actual speed could track the reference speed showing the robustness of the drive controllers, we can say that the dynamic speed response is fast in Case of DTC as compared to DFOC. The DTC presents a high dynamics at starting instant and rapid load torque disturbance rejection without overshoot compared to the DFOC. DTC is a better choice as compared to DFOC as far as speed response is considered.

Figure 9 show the phase current for DFOC and DTC, here a significant difference between the methods where, one can observe that The DTC presents a more oscillating current at starting.

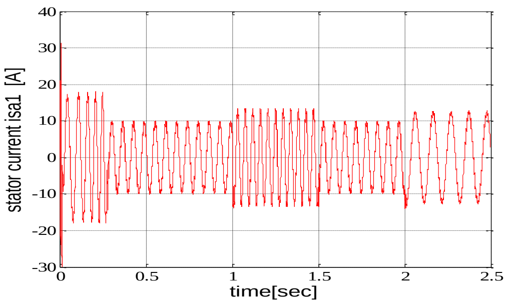



(a) **DFOC**

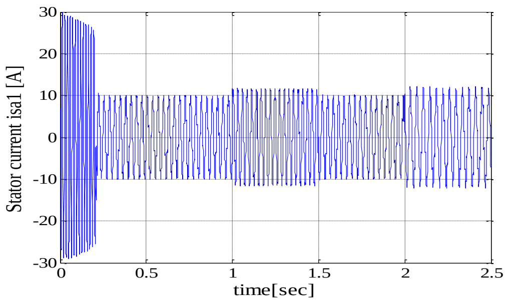



**(b) DTC**

***Figure 08: Regulation of speed followed by an application of torque load at the t = 1 s and t= 2s (a) DFOC scheme, (b) DTC scheme***



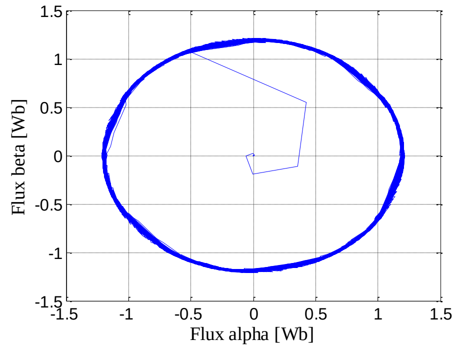

(a) **DFOC**



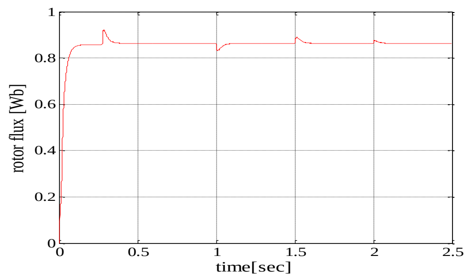

**(b) DTC**

***Figure 09 Shape of the current phase of the stator 1, (a) DFOC scheme, (b) DTC scheme***

The trajectory of $\phi\alpha$ and $\phi\beta$ is a circle as expected that is shown on figure 10




***a) DTC***



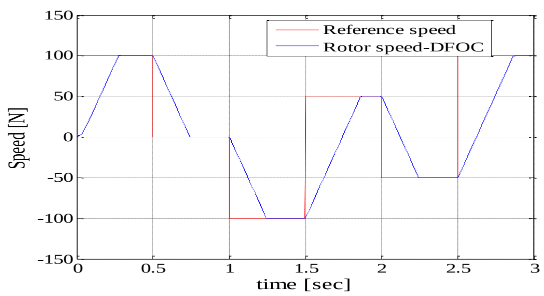

***(b) DFOC***

***Figure 10 :***

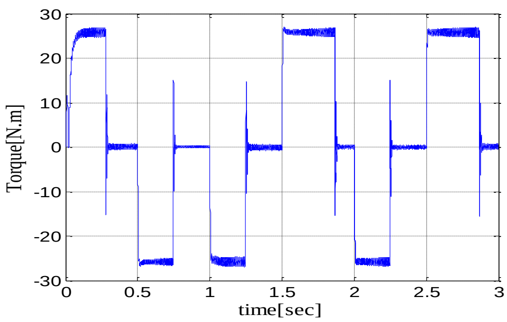
***(a)The trajectory of the stator flux vector of DTC scheme***

***(b) Rotor flux response of DFOC scheme***

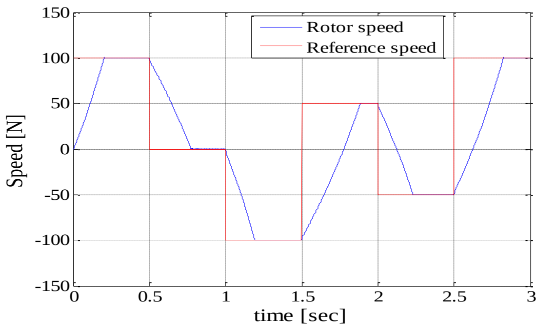
To test the robustness of both technical command at the reverse direction of rotation, it introduced a change in record speed reference +100 rad/s to -100 rad/s. then 50 rad/s to -50 rad/s (figure11), we can say that the continuation in speed is normally and without overrun for both technical commands (DTC and DFOC). It notes that the DTC presents a peak torque than the DFOC



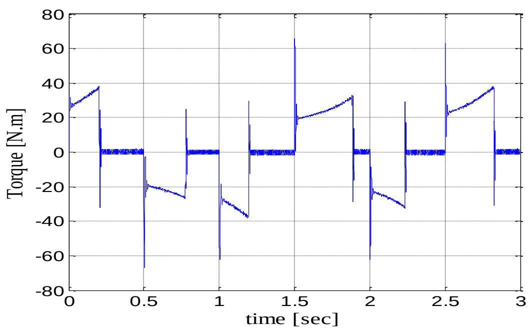

(a)




(b)




***(c)***




***(d)***

***Figure 12: Four quadrant speed estimation and torque stator:***

***(a) and (b) DFOC scheme***

***(c) and (d) DTC scheme***

## 5 SUMMARY

In summary, DTC provides a better dynamic torque response, whereas the DFOC provides a better steady state behavior

DTC might be preferred for high dynamic applications, but shows higher current and torque ripple. Unlike DFOC, DTC does not require any current regulator, coordinate transformation and PWM signals generator (as a consequence timers are not required). In spite of its simplicity, DTC allows a good torque control in steady-state and transient operating conditions to be obtained. The basic DTC scheme is more suitable in the small and medium power range applications.

It can be concluded therefore that both techniques offer similar levels of machine performance, each with particular advantages and disadvantages. Table 2 shows the comparison between DFOC and DTC methods

***Table 02: Summary of Comparison; Schemes and Results***

| | DFOC | DTC |
|---|---|---|
| algorithm complexity | **middle** | **low** |
| Decoupling | **Require** | **orientation Natural** |
| Control close | **Nessary PWM** | **Not of PWM** |
| Speed sensor | **necessary** | **Less necessary** |
| Switching frequency | **Constant** | **Variable** |
| Regulators | **Three stator regulator (Hysteresis)** | **-Torque regulator -Flux regulator** |
| Torque ripple under | **Low** | **High** |
| stator flux ripple | **Low** | **High** |
| Dynamic response | **High** | **High** |
| Parameter sensitivity | **High** | **average** |
| Robustness | **Robust** | **Robust** |
| Behavior down Speed | **Good** | **not good** |

## *6* CONCLUSION

The aim of the paper was to give a fair comparison between DFOC and DTC techniques, the proposed techniques has been applied to dual star induction motor, in conclusion, it can be said that both methods provide a high performance response with quicker torque dynamics and less sensitivity to machine parameters in the case of DTC and better steady-state behavior for DFOC. The DTC might be preferred for high dynamic applications, but shows higher current and torque ripple. Depending on the requirements of a particular application one method can be more convenient than the other.

***Table 03: 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 |

## REFERENCES

**[1]** D. Hadiouche, " Contribution à l'etude de la machine asynchrone double etoile : Modélisation, alimentation et structure", These de doctorat de l'Universite Henri Poincare, Nancy-1., 2001.

**[2]** Krzysztof Pieńkowski," Analysis and control of dual stator winding induction motor", archives of electrical engineering vol. 61(3), pp. 421-438, mars 2012

**[3]** Raúl Igmar Gregor Recalde " The Asymmetrical Dual Three-Phase Induction Machine and the MBPC in the Speed Control, Induction Motors - Modelling and Control", Prof. Rui Esteves Araújo (Ed.), InTech, DOI: 10.5772/50559.november 2012

**[4]** Levi, e " Multiphase electric machines for variable-speed applications" IEEE Transactions on industrial electronics, vol. 55, no. 5, pp.1893-1909, may 2008, issn 0278-0046

**[5]** I. Takahashi, T. Noguchi, "A New Quick-Response and high Efficiency Control Strategy of an Induction Motor", IEEE Trans. on IA, vol. 22, No. 5, Sept/Oct. 1986.

**[6]** S.Lekhchine, T.Bahi, Y. Soufi" Direct Torque Control of Dual Star Induction Motor", International Journal Of Renewable Energy Research, Vol.3, No.1, 2013

**[7]** A. Yazidi, A. Pantea, M. Taherzahed, S. Carriere, F. Betin, H. Henao, and G.A. Capolino," Six-phase induction machine model for fault simulation and control purposes using the circuit-oriented approach," IEEE Trans. on Ind. Electron., vol. 63, no. 1, January 2016.

**[8]** D.Ziane, A.Azib, N.Taib,T.REKIOUA, "Study and Design of the direct torque control of Double star induction motor", Journal of Electrical Systems, pp114-124, 2013.

**[9]** F.Blaschke "The Principle of Field Orientation Applied to The New Transvector Closed-Loop Control System for Rotating Field Machines", Siemens-Rev., Vol. 39, 217–220, 1972.

**[10]** B. Kundrotas, S. Lisauskas, R. Rinkeviciene. "Model of Multiphase Induction Motor", Electronics and Electrical Engineering. – Kaunas: Technologija,. No. 5(111). – pp. 111–114, feb 2011

**[11]** H.Le-Huy, " Comparison of field-oriented control and direct torque control for induction motor drives", Industry Applications Conference, 34h IAS Annual Meeting. Conference Record of the 1999 IEEE

**[12]** A..Azib, D. Ziane, T.Rekioua, A.Tounzi," Robustness Of The Direct Torque Control Of Double Star Induction Motor In Fault Condition", Rev. Roum. Sci. Techn.– Électrotechn. et Énerg. Vol. 61, 2, pp. 147–152, Bucarest, 2016

**[13]** S.Belkacem,, L.Laggoune, B.Kiyyour, "A Novel Speed Sensorless DTC For Induction Motor Based On An Improvrd Adptive Flux Observer" IEEE International Symposium on industrial Electronics-ISIE 2005,Dubrovnik,Croatia

**[14]** S.Chacko, Chandrashek N.Bhende, Shailendra Jain and R.K. Nema," Modeling And Simulation Of Field Oriented Control Induction Motor Drive And Influence Of Rotor Resistance Variations On Its Performance", Electrical and Electronics Engineering: An International Journal (ELELIJ) Vol 5, No 1, February 2016

**[15]** Fatih Korkmaz, " Speed And Torque Control Of An Induction Motor With Ann Based DTC ", International Journal Of Instrumentation And Control Systems (IJICS) Vol.7, No.1, January 2017

**[16]** A.Thiab Humod , M.d Najm Abdullah , L. Fatma H. Faris," A Comparative Study between Vector Control and Direct Torque Control of Induction Motor Using Optimal Controller," International Journal of Scientific & Engineering Research, Volume 7, Issue 4, April-2016