Performances comparative study of Field Oriented Control (FOC) and Direct Torque Control (DTC) of Dual Three Phase Induction Motor (DTPIM)

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Abstract— We present in this paper a comparative study between two most popular control strategies of electrical machines: field oriented control (FOC) and direct torque control (DTC) for controlling a Dual Three Phase Induction Motor. The comparison is based on several criteria including: static and dynamic performance, structure and implementation complexity, decoupling, torque and current ripple, etc... Also, we present in this study the advantages and disadvantages of each control scheme, the best is the one that better meets the requirements.

Keywords— Dual Three Phase Induction Motor (DTPIM), Field Oriented Control (FOC), Direct Torque Control (DTC).

I. INTRODUCTION

In the industrial applications that high reliability is demanded, multi-phase induction machine instead of traditional three-phase induction machine is used. A common type of multiphase machine is the dual three phase induction machine (DTPIM),is also known as the six phase induction machine, these machines have been used in many applications (pumps, fans, compressors, rolling mills, cement mills, mine hoists …[1]) for their advantages in power segmentation, reliability, and minimized torque pulsations. Such segmented structures are very attractive for high-power applications, since they allow the use of lower rating power electronic devices at a switching frequency higher than the one usually used in three-phase ac machine drives [2].

In the last decade high performance drives based on the spatial position of the flux and on space vector theory have been developed and industrially applied. Nowadays two groups of usually applied control schemes can be distinguished: Field Oriented Control (FOC) and Direct Torque Control (DTC) [3].

The main difficulty in the asynchronous machine control resides in the fact that complex coupling exists between the field and the torque. The field oriented control assures decoupling between these variables, and it is used to simplify the speed control of induction motors (IMs), so they can be controlled like a separately excited direct current (DC) machine [4], [5].

The direct torque control (DTC) method was proposed in the middle of 1980 by I.Takahashi [6], this method has become one of the high performance control strategies for AC machine to provide a very fast torque and flux control. The name direct torque control is derived by the fact that, on the basis of the errors between the reference and the estimated values of torque and flux, it is possible to directly control the inverter states in order to reduce the torque and flux errors within the prefixed band limits [7], [8].

This paper is organized in six sections. The DTPIM model is presented in the next section. The control method by FOC and DTC will be discussed in section three and four. In the fifth and sixth section we present the simulation results and comparison of two control schemes. Finally, a general conclusion summaries this work. The simulation results are obtained by using Matlab/Simulink.

II. DTPIM MODEL

A schematic of the stator and rotor windings for a machine dual three phase is given in Fig. 1. The six stator phases are divided into two wyes-connected three phase sets labeled A_{s1}, B_{s1}, C_{s1} and A_{s2}, B_{s2}, C_{s2} whose magnetic axes are displaced by an angle α=30°. The windings of each three phase set are uniformly distributed and have axes that are displaced 120° apart. The three phase rotor windings A_r, B_r, C_r are also sinusoidally distributed and have axes that are displaced apart by 120° [9] [10].

The following assumptions are made: [4], [11]:

- Motor windings are sinusoidally distributed;
- The two stars have same parameters;
- The magnetic saturation, the mutual leakage inductances and the core losses are negligible;
- Flux path is linear.

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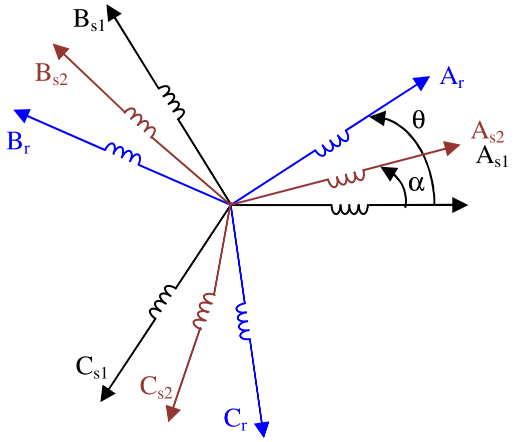


Fig. 1 Windings of the dual star induction machine

The voltage equations of the dual star induction machine are as follow [12] [13]:

$$[V_{s1}]=\begin{bmatrix}V_{sa1}\\V_{sb1}\\V_{sc1}\end{bmatrix}=[R_{s1}][I_{s1}]+\frac{d}{dt}[\Phi_{s1}]$$

$$[V_{s2}]=\begin{bmatrix}V_{sa2}\\V_{sb2}\\V_{sc2}\end{bmatrix}=[R_{s2}][I_{s2}]+\frac{d}{dt}\left[\Phi_{s2}\right] \qquad (1)$$

$$[0]=\begin{bmatrix}V_{ra}\\V_{rb}\\V_{rc}\end{bmatrix}=[R_r][I_r]+\frac{d}{dt}[\Phi_r]$$

Where:
$R_{sa1}=R_{sb1}=R_{sc1}=R_{s1}$: Stator resistance 1.
$R_{sa2}=R_{sb2}=R_{sc2}=R_{s2}$: Stator resistance 2.
$R_{ra}=R_{rb}=R_{rc}=R_r$: Rotor resistance.

$$[I_{s1}]=\begin{bmatrix}I_{sa1}\\I_{sb1}\\I_{sc1}\end{bmatrix};\ [I_{s2}]=\begin{bmatrix}I_{sa2}\\I_{sb2}\\I_{sc2}\end{bmatrix};[I_r]=\begin{bmatrix}I_{ra}\\I_{rb}\\I_{rc}\end{bmatrix} \qquad (2)$$

$$[\Phi_{s1}]=\begin{bmatrix}\Phi_{sa1}\\\Phi_{sb1}\\\Phi_{sc1}\end{bmatrix};[\Phi_{s2}]=\begin{bmatrix}\Phi_{sa2}\\\Phi_{sb2}\\\Phi_{sc2}\end{bmatrix};[\Phi_r]=\begin{bmatrix}\Phi_{ra}\\\Phi_{rb}\\\Phi_{rc}\end{bmatrix} \qquad (3)$$

The expressions for stator and rotor flux are [12]:

$$\begin{bmatrix}[\Phi_{s1}]\\[\Phi_{s2}]\\[\Phi_r]\end{bmatrix}=\begin{bmatrix}[L_{s1s1}] & [L_{s1s2}] & [L_{s1r}]\\ [L_{s2s1}] & [L_{s2s2}] & [L_{s2r}]\\ [L_{rs1}] & [L_{rs2}] & [L_{rr}]\end{bmatrix}.\begin{bmatrix}[I_{s1}]\\[I_{s2}]\\[I_r]\end{bmatrix} \qquad (4)$$

Where:
$[L_{s1s1}]$: Inductance matrix of the star 1.
$[L_{s2s2}]$: Inductance matrix of the star 2.
$[L_{rr}]$: Inductance matrix of the rotor.
$[L_{s1s2}]$: Mutual inductance matrix between star 1 and star 2.
$[L_{s2s1}]$: Mutual inductance matrix between star 2 and star 1.
$[L_{s1r}]$: Mutual inductance matrix between star 1 and rotor.
$[L_{s2r}]$: Mutual inductance matrix between star 2 and rotor.
$[L_{rs1}]$: Mutual inductance matrix between rotor and star 1.
$[L_{rs2}]$: Mutual inductance matrix between rotor and star 2.

The expression of the electromagnetic torque is then as follows [1] [12] [14]:

$$T_{em}=\left(\frac{p}{2}\right).\left([I_{s1}]\frac{d}{d\theta}[L_{s1r}].[I_r]+[I_{s2}]\frac{d}{d\theta}[L_{s2r}][I_r]\right) \qquad (5)$$

The Park model of the dual star induction machine in the references frame at the rotating field (d, q), is defined by the following equations system (6) [9].
The figure 2 represents the model of the DSIM in the Park frame.

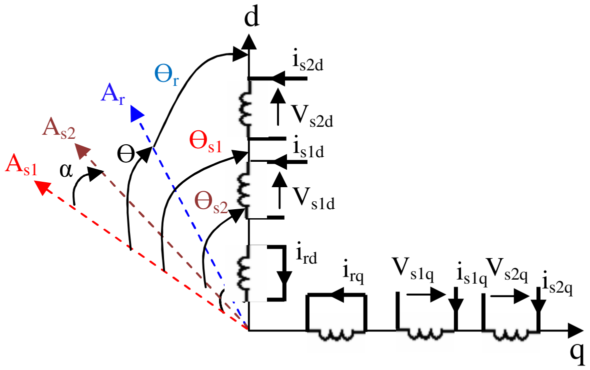


Fig. 2 Representation of DTPIM in the Park frame

$$\begin{aligned}
V_{s1d} &= R_{s1}I_{s1d}+\frac{d}{dt}\Phi_{s1d}-\omega_s\Phi_{s1q}\\
V_{s1q} &= R_{s1}I_{s1q}+\frac{d}{dt}\Phi_{s1q}+\omega_s\Phi_{s1d}\\
V_{s2d} &= R_{s2}I_{s2d}+\frac{d}{dt}\Phi_{s2d}-\omega_s\Phi_{s2q}\\
V_{s2q} &= R_{s2}I_{s2q}+\frac{d}{dt}\Phi_{s2q}+\omega_s\Phi_{s2d}\\
0 &= R_rI_{rd}+\frac{d\Phi_{rd}}{dt}-\omega_{sr}\Phi_{rq}\\
0 &= R_rI_{rq}+\frac{d\Phi_{rq}}{dt}+\omega_{sr}\Phi_{rd}
\end{aligned} \qquad (6)$$

Where:

$$\begin{aligned}
\Phi_{s1d} &= L_{s1} I_{s1d} + L_m (I_{s1d} + I_{s2d} + I_{rd}) \\
\Phi_{s1q} &= L_{s1} I_{s1q} + L_m (I_{s1q} + I_{s2q} + I_{rq}) \\
\Phi_{s2d} &= L_{s2} I_{s2d} + L_m (I_{s1d} + I_{s2d} + I_{rd}) \\
\Phi_{s2q} &= L_{s2} I_{s2q} + L_m (I_{s1q} + I_{s2q} + I_{rq}) \\
\Phi_{rd} &= L_r I_{rd} + L_m (I_{s1d} + I_{s2d} + I_{rd}) \\
\Phi_{rq} &= L_r I_{rq} + L_m (I_{s1q} + I_{s2q} + I_{rq})
\end{aligned} \tag{7}$$

L_m: Cyclic mutual inductance between stator 1, stator 2 and rotor.

The mechanical equation is given by:

$$J \frac{d\Omega}{dt} = T_{em} - T_r - F_r \Omega \tag{8}$$

With:

$$T_{em} = p \frac{L_m}{L_r + L_m} \left[\Phi_{rd}(I_{s1q} + I_{s2q}) - \Phi_{rq}(I_{s1d} + I_{s2d}) \right] \tag{9}$$

III. Voltage Source Inverter Modeling

The voltage source inverter (VSI) is a static converter constituted by switching cells generally with transistors or thyristors GTO for high powers (Fig.3). The operating principle can be expressed by imposing on the machine the voltages with variable amplitude and frequency starting from a standard network 220/380v-50Hz [15].Voltages at load neutral point can be given by the following expression [16]:

$$\begin{bmatrix} V_{an} \\ V_{an} \\ V_{an} \end{bmatrix} = \frac{E}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} K_{11} \\ K_{12} \\ K_{13} \end{bmatrix} \tag{10}$$

This modeling for the two converters that feed the DTPIM.

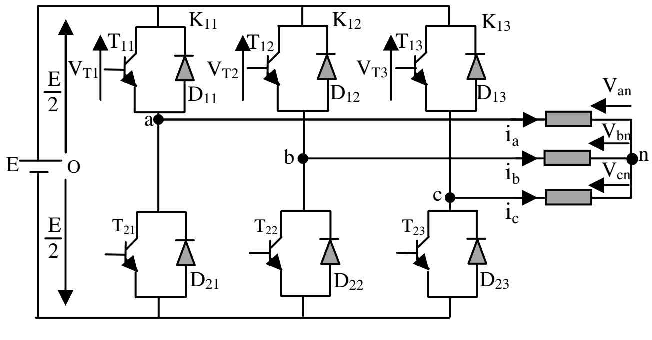


Fig. 3 Voltage Source Inverter scheme

IV. Field Oriented Control

The objective of space vector control is to assimilate the operating mode of the asynchronous machine at the one of a DC machine with separated excitation, by decoupling the torque and the flux control. The FOC consists in making $\Phi_{rq}=0$ while the rotor direct flux Φ_{rd} converges to the reference Φ_r^* [4], [16]. In the Direct Field Oriented Control (Modified FOC), the rotor flux modulus will be controlled by feedback. An estimator of rotor flux Φ_r is implanted from currents measurements (*isd* and *isq*), and rotor currents pulsation ω_r imposed on the machine (Fig.4). By applying this principle ($\Phi_{rq}=0$ *and* $\Phi_{rd} = \Phi_r^*$) to equations (6) (7) and (9), the finals expressions of the electromagnetic torque and slip speed are:

$$T_{em} = p \frac{L_m}{L_m + L_r} \Phi_r^* (I_{s1q}^* + I_{s2q}^*) \tag{11}$$

$$w_{sr}^* = \frac{R_r L_m}{(L_m + L_r)\Phi_r^*} (I_{s1q}^* + I_{s2q}^*) \tag{12}$$

The stators voltage equations are:

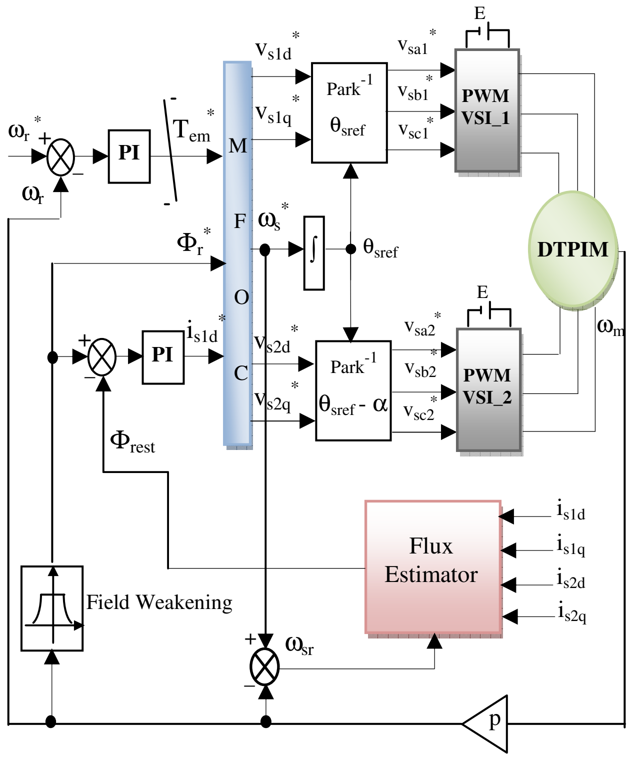


Fig. 4 Direct method speed regulation

$$\begin{aligned}
\overset{*}{V}_{s1d} &= R_{s1}I_{s1d} + L_{s1}\frac{d}{dt}I_{s1d} - \overset{*}{\omega}_s\left(L_{s1}I_{s1q} + T_r\overset{*}{\Phi}_r\overset{*}{w}_{sr}\right)\\
\overset{*}{V}_{s1q} &= R_{s1}I_{s1q} + L_{s1}\frac{d}{dt}I_{s1q} + \overset{*}{\omega}_s\left(L_{s1}I_{s1d} + \overset{*}{\Phi}_r\right)\\
\overset{*}{V}_{s2d} &= R_{s2}I_{s2d} + L_{s2}\frac{d}{dt}I_{s2d} - \overset{*}{\omega}_s\left(L_{s2}I_{s2q} + T_r\overset{*}{\Phi}_r\overset{*}{w}_{sr}\right)\\
\overset{*}{V}_{s2q} &= R_{s2}I_{s2q} + L_{s2}\frac{d}{dt}I_{s2q} + \overset{*}{\omega}_s\left(L_{s2}I_{s2d} + \overset{*}{\Phi}_r\right)
\end{aligned} \tag{13}$$

The torque expression shows that the reference fluxes and stator currents in quadrate are not perfectly independent, for this, it is necessary to decouple torque and flux control of this machine by introducing new variables:

$$\begin{aligned}
V_{s1d} &= R_{s1}I_{s1d} + L_{s1}\frac{d}{dt}I_{s1d}\\
V_{s1q} &= R_{s1}I_{s1q} + L_{s1}\frac{d}{dt}I_{s1q}\\
V_{s2d} &= R_{s2}I_{s2d} + L_{s2}\frac{d}{dt}I_{s2d}\\
V_{s2q} &= R_{s2}I_{s2q} + L_{s2}\frac{d}{dt}I_{s2q}
\end{aligned} \tag{14}$$

The equation system (14) shows that stator voltages $(V_{s1d}, V_{s1q}, V_{s2d}, V_{s2q})$ are directly related to stator currents $(I_{s1d}, I_{s1q}, I_{s2d}, I_{s2q})$. To compensate the error introduced at decoupling time, the voltage references $(V_{s1d}^*, V_{s2d}^*, V_{s1q}^*, V_{s2q}^*)$ at constant flux are given by:

$$\begin{aligned}
V_{s1d}^* &= V_{s1d} - V_{s1dc}\\
V_{s1q}^* &= V_{s1q} + V_{s1qc}\\
V_{s2d}^* &= V_{s2d} - V_{s2dc}\\
V_{s2q}^* &= V_{s2q} + V_{s2qc}
\end{aligned} \tag{15}$$

With:

$$\begin{aligned}
V_{s1dc} &= \overset{*}{\omega}_s\left(L_{s1}I_{s1q} + T_r\overset{*}{\Phi}_r\overset{*}{w}_{sr}\right)\\
V_{s1qc} &= \overset{*}{\omega}_s\left(L_{s1}I_{s1d} + \overset{*}{\Phi}_r\right)\\
V_{s2dc} &= \overset{*}{\omega}_s\left(L_{s2}I_{s2q} + T_r\overset{*}{\Phi}_r\overset{*}{w}_{sr}\right)\\
V_{s2qc} &= \overset{*}{\omega}_s\left(L_{s2}I_{s2d} + \overset{*}{\Phi}_r\right)
\end{aligned} \tag{16}$$

For a perfect decoupling, we add stator currents regulation loops $(I_{s1d}, I_{s1q}, I_{s2d}, I_{s2q})$ and we obtain at their output stator voltages $(V_{s1d}, V_{s1q}, V_{s2d}, V_{s2q})$.The decoupling bloc scheme in voltage modified (Modified Field Oriented Control) is given in Fig.5.

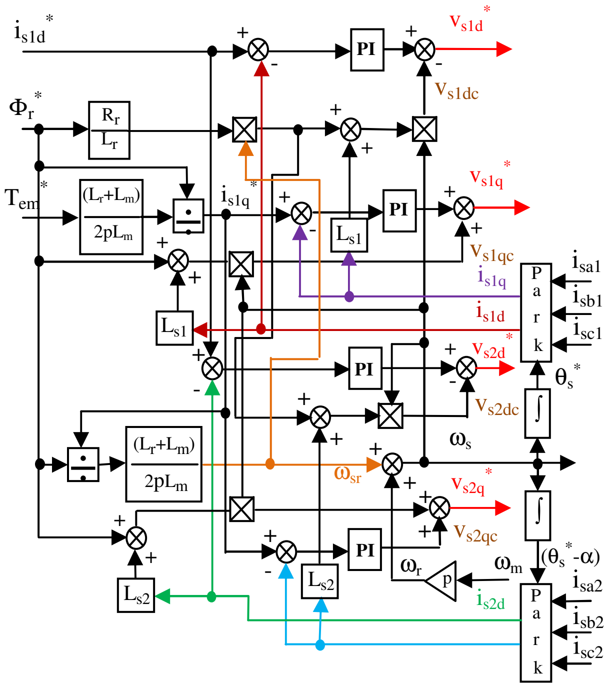
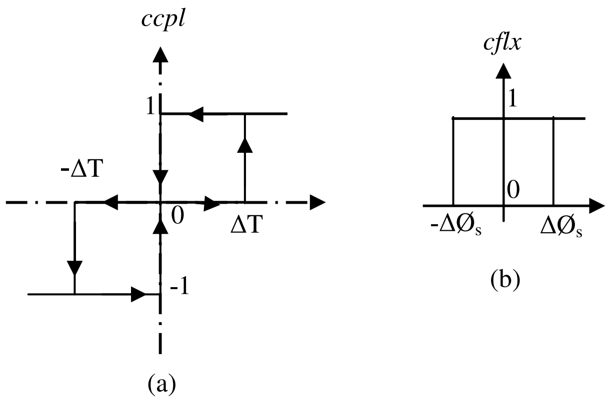


Fig. 5 Decoupling bloc in voltage modified

V. Direct Torque Control

The Direct Torque Control (DTC) method allows direct and independent electromagnetic torque and flux control, selecting an optimal switching vector [17]. The Fig.6 shows a block diagram of the DTC scheme applied to the DTPIM. The reference values of flux (Φ_s^*) and torque (T_{em}^*) are compared to their actual values and the resultant errors are fed into a two level hysteresis comparator for the flux and three level hysteresis comparator for the torque, who allows controlling the motor in the two directions of rotation (Fig.7).



(a)

(b)

Fig. 7 Hysteresis comparator, (a): three level hysteresis comparator for the torque, (b): two level hysteresis comparator for the flux

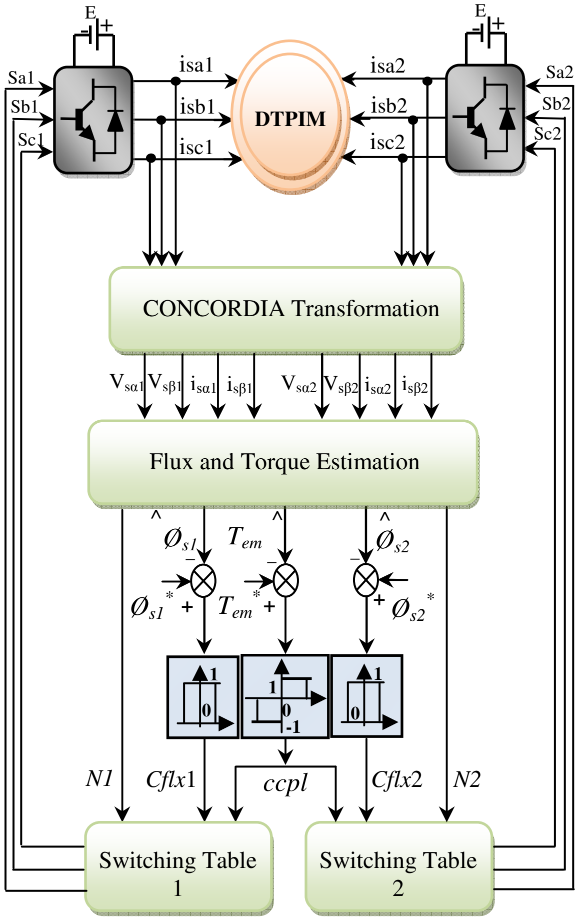


Fig. 6 Block diagram of Direct Torque Control for DTPIM

For the stator flux vector laying in sector 1 (Fig.8), in order to increase its magnitude, the voltage vectors V_1, V_2, and V_6 can be selected. Conversely, a decrease can be obtained by selecting V_3, V_4 and V_5. However, to increase the electromagnetic torque the voltage vectors V_2, V_3 and V_4 can be selected and a decrease can be obtained by the vectors**:** V_1, V_5 and V_6.

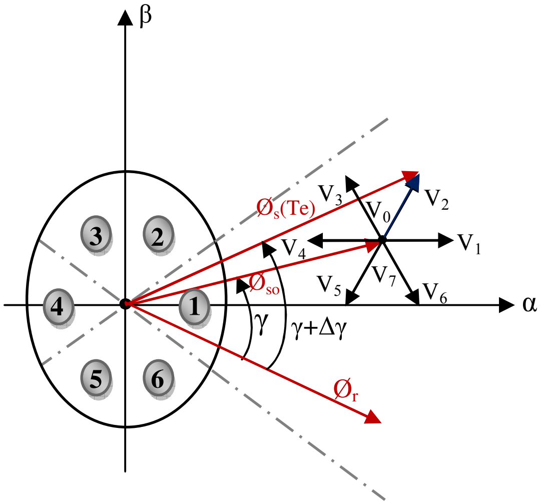


Fig. 8 Voltage vector selection

The stator flux and the electromagnetic torque expression are given by [18]:

$$\phi_s(Te) = Vs + \phi_{so} \tag{17}$$

$$T_{em} = Kc\,.\left\|\overrightarrow{\phi_s}\right\|.\left\|\overrightarrow{\phi_r}\right\|\sin(\gamma) \tag{18}$$

K_c: constant depending on the parameters of the machine.
γ: Angle between the two vectors stator and rotor flux.

The application of zero voltage vectors (V_0 and V_7) stops the rotation of the stator flux vector Φ_s. However, the rotor flux Φ_r continues its evolution and try to catch up the stator flux. Thus, the angle γ between stator and rotor flux will decrease and the electromagnetic torque decreases slowly.

VI. SWITCHING STRATEGY

The switching table allows to select the appropriate inverter switching state according to the state of hysteresis comparators of flux *(cflx)* and torque *(ccpl)* and the sector where is the stator vector flux (Φ_s) in the plan *(α, β)*, in order to maintain the magnitude of stator flux and electromagnetic torque inside the hysteresis bands. The above consideration allows construction of the switching table as presented in Table I.

Table I. Switching table with zero voltage vectors

Sectors				1	2	3	4	5	6
cflx	0	ccpl	1	V_3	V_4	V_5	V_6	V_1	V_2
			0	V_0	V_7	V_0	V_7	V_0	V_7
			-1	V_5	V_6	V_1	V_2	V_3	V_4
cflx	1	ccpl	1	V_2	V_3	V_4	V_5	V_6	V_1
			0	V_7	V_0	V_7	V_0	V_7	V_0
			-1	V_6	V_1	V_2	V_3	V_4	V_5

VII. SIMULATION RESULTS

The simulation results of Direct Field Oriented Control (DFOC) and Direct Torque Control of Dual Three Phase Induction Motor are given in Fig.9 and Fig.10.

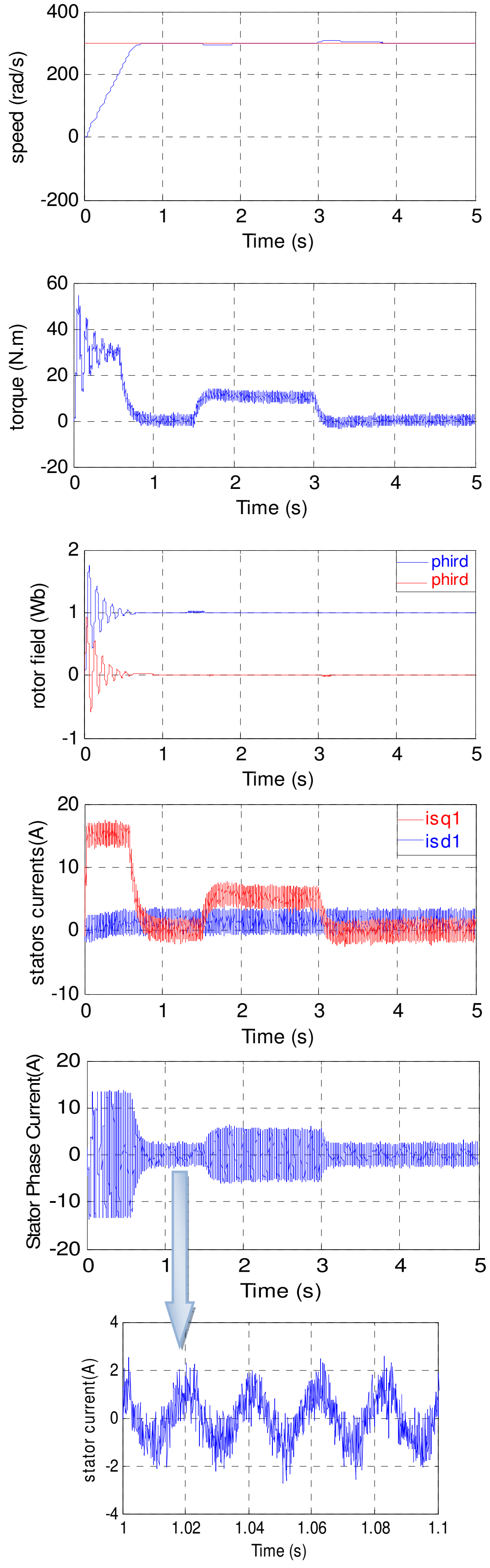


Fig.9 DFOC Speed regulation with load torque (10 N.m) between [1.5 3] s

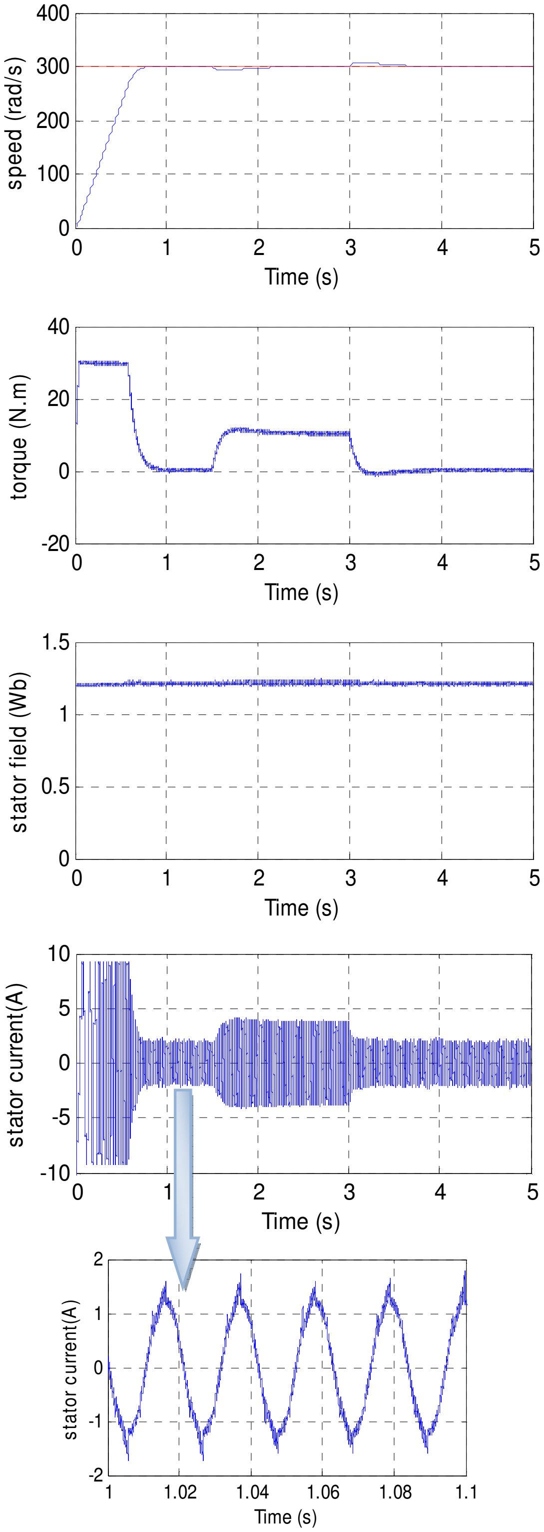


Fig. 10 DTC of DTPIM with load torque (10 N.m) between [1.5 3] s

The table II summaries the principal differences between Field Oriented Control (FOC) and Direct Torque Control (DTC) [18], [19], [20].

Table II. Comparison of FOC and DTC schemes

	FOC	*DTC*
Decoupling	Require orientation	Natural
PWM	Required	Not Required
Coordinates reference frame	Reference frame (d_q)	Reference frame (α_β)
Controlled variables	Torque and rotor flux	Torque and stator flux
Regulators	Three stator current PI regulators	Two Hysteresis regulator (torque and stator flux)
Switching frequency	Constant	Variable
Switching losses	Low	higher
Torque response	Good	Very good
Torque and Flux control	Indirectly controlled by stator currents	Directly controlled
Flux dynamic	Slow	Fast
Implementation complexity	High complexity	Less complexity

VII.CONCLUSION

In this paper, the principle and a several characteristics of Field Oriented and Direct Torque Control schemes for Dual Three Phase Induction Motor drive are studied by simulation in order to determinate the main advantages and drawbacks of each control and to make a comparison between them.

The field oriented control (FOC) is based on an analogy to the separately excited DC motor, where the flux and torque can be controlled independently. In this control scheme, the torque is controlled indirectly by the stator current component.

The Direct Torque Control (DTC) allows direct and independent electromagnetic torque and flux control, selecting an optimal switching vector, making possible fast torque response, low inverter switching frequency and low harmonic losses. However, two major problems associated with DTC drive: electromagnetic torque ripple and variable switching frequency.

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APPENDIX

Table I. DTPIM Parameters

P_n [kw]	4.5	R_r [Ω]	2 .12	J [kg.m²]	0.0625
V_n [V]	220	L_{s1} [H]	0.022	K_f [Nms/r]	0.001
I_n [A]	6.5	L_{s2} [H]	0.022	f [Hz]	50
R_{s1} [Ω]	3.72	L_r [H]	0.006	p	1
R_{s2} [Ω]	3.72	L_m [H]	0.367	Cos φ	0.8

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