Study and Simulation of Direct Torque Control (DTC) for a Six Phase Induction Machine (SPIM)

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***Abstract*—**This paper presents a performances study of a Direct Torque and Flux Control (DTC) for a Six Phase Induction Machine (SPIM) dedicated to electrical drives using a two level voltage source inverter (VSI). This method has become one of the high performance control strategies for AC machine to provide a very fast torque and flux control. The simulation results show the effectiveness of the proposed method in both dynamic and steady state response.

***Keywords*—** Six Phase Induction Machine (SPIM), Direct Torque Control (DTC), Voltage Source Inverter (VSI), Hysteresis comparator.

I. Introduction

THE power rating of an AC drive system can be increased by using high phase order drive system (multiphase machine) which has more than three phases in the stator of the machine. High phase order drive systems possess several advantages over conventional three-phase drives, such as reducing the amplitude and increasing the frequency of torque pulsation, reducing the rotor harmonic currents, reducing the current per phase without increasing the voltage per phase, and lowering the DC-Link current harmonics and high reliability. Otherwise, losing of one or more phases in a high phase order drive system does not prevent the machine from starting and running [1].

A common type of multiphase machine is the Six Phase Induction Machine (SPIM), also known as the dual star induction machine. This machine has been used in many applications where high reliability and high power is demanded such as aerospace applications, electric/hybrid vehicles, ship propulsion, rolling mills, cement mills, mine hoists … etc [1], [2].

The direct torque control (DTC) method was proposed in the middle of 1980 by I.Takahashi [3], 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 [4], [5].

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

II. SPIM Model

If 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 As1, Bs1, Cs1 and As2, Bs2, Cs2 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 Ar, Br, Cr are also sinusoidally distributed and have axes that are displaced apart by 120° [6], [7].

The following assumptions are made: [8], [9]:

-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.

The voltage equations of the dual star induction machine are as follow [10], [11]:

$$\begin{aligned}
&[V_{s1}] = \begin{bmatrix} V_{sa1} \\ V_{sb1} \\ V_{sc1} \end{bmatrix} = [R_{s1}][I_{s1}] + \frac{d}{dt}[\Phi_{s1}] \\
&[V_{s2}] = \begin{bmatrix} V_{sa2} \\ V_{sb2} \\ V_{sc2} \end{bmatrix} = [R_{s2}][I_{s2}] + \frac{d}{dt}[\Phi_{s2}] \\
&[0] = \begin{bmatrix} V_{ra} \\ V_{rb} \\ V_{rc} \end{bmatrix} = [R_{r}][I_{r}] + \frac{d}{dt}[\Phi_{r}]
\end{aligned} \tag{1}$$

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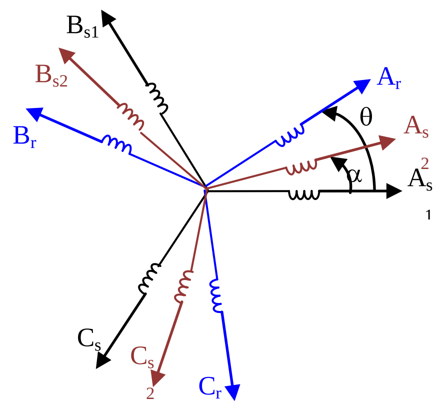


Fig. 1 Windings of the Six Phase Induction Machine

Where:
Rsa1 = Rsb1 = Rsc1 = Rs1: Stator resistance 1.
Rsa2 = Rsb2 = Rsc2 = Rs2: Stator resistance 2.
Rra = Rrb = Rrc = Rr: Rotor resistance.

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

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

The expressions for stator and rotor flux are [10]:

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

Where:
[Ls1s1]: Inductance matrix of the star 1.
[Ls2s2]: Inductance matrix of the star 2.
[Lrr]: Inductance matrix of the rotor.
[Ls1s2]: Mutual inductance matrix between star 1and star 2.
[Ls2s1]: Mutual inductance matrix between star 2and star 1.
[Ls1r]: Mutual inductance matrix between star 1 and rotor.
[Ls2r]: Mutual inductance matrix between star 2 and rotor.
[Lrs1]: Mutual inductance matrix between rotor and star 1.
[Lrs2]: Mutual inductance matrix between rotor and star 2.

The expression of the electromagnetic torque is then as follows [10],[12], [13]:

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

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

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) [6].

The figure 2 represents the model of the SPIM in the Park frame.

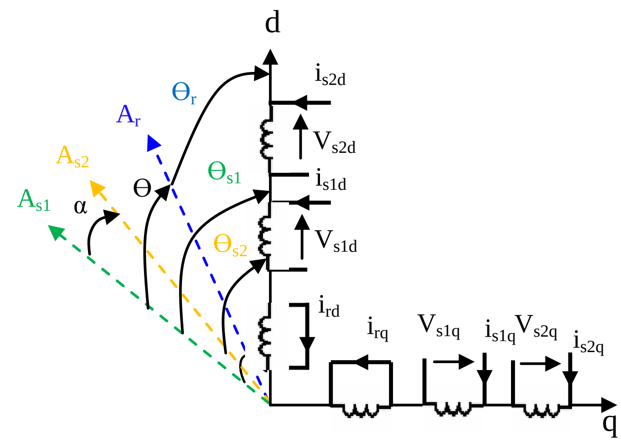


Fig. 2 Representation of SPIM in the Park frame

Where:

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

Lm: 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. DIRECT TORQUE CONTROL

The Direct Torque Control (DTC) method allows direct and independent electromagnetic torque and flux control, selecting an optimal switching vector [14]. The Fig.3 shows a block diagram of the DTC scheme applied to the SPIM. The reference values of flux (Φs*) and torque (Tem*) 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.4).

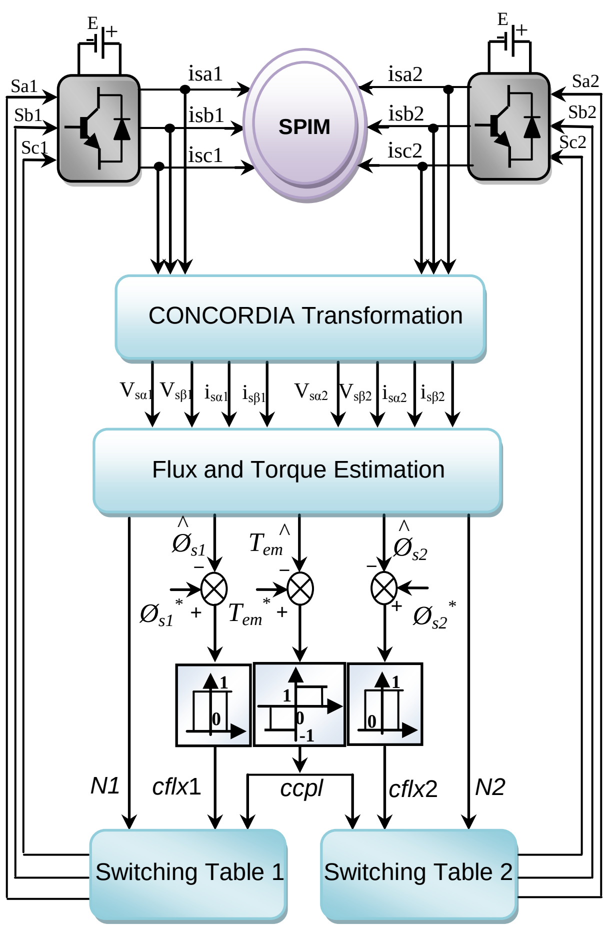


Fig. 3 Block diagram of Direct Torque Control for SPIM

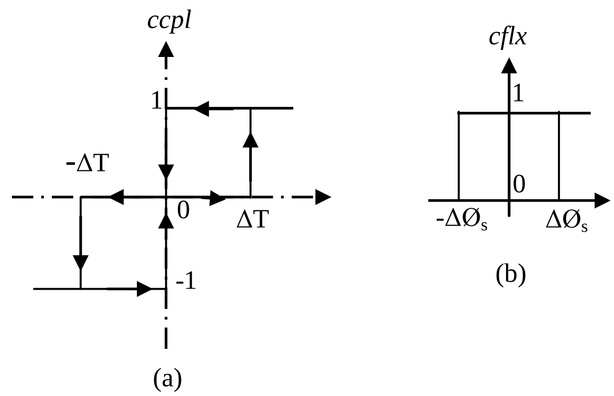


Fig. 4 Hysteresis comparator, (a): three level hysteresis comparator for the torque, (b): two level hysteresis comparator for the flux

For the stator flux vector laying in sector 1 (Fig.5), in order to increase its magnitude, the voltage vectors V1, V2, and V6 can be selected. Conversely, a decrease can be obtained by selecting V3, V4 and V5. However, to increase the electromagnetic torque the voltage vectors V2, V3 and V4 can be selected and a decrease can be obtained by the vectors: V1, V5 and V6.

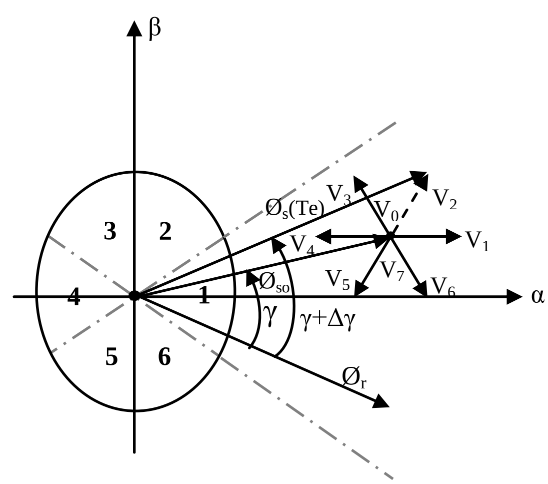


Fig. 5 Voltage vector selection

The stator flux and the electromagnetic torque expression are given by [15]:

$$\phi_s(Te) = Vs + \phi_{so} \tag{10}$$

$$T_{em} = Kc.\left\|\overrightarrow{\phi_s}\right\|.\left\|\overrightarrow{\phi_r}\right\|\sin(\gamma) \tag{11}$$

Kc: 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 Φs. However, the rotor flux Φr 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.

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 (Φs) 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 1.

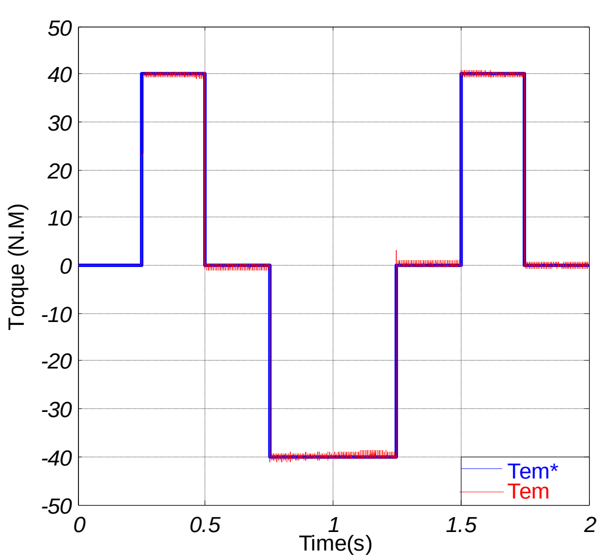
Table 1: Switching table with zero voltage vectors

sectors				$N=1$	$N=2$	$N=3$	$N=4$	$N=5$	$N=6$
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

IV. SIMULATION RESULTS

In order to test the validity of the direct torque control, and to prove that the speed follows the variations of the torque, we removed the regulation loop speed and we imposed a reference torque, the results obtained are shown in Figure 6.

The simulation results show that the stator current (isa1) has a good response to the variations imposed by the torque, and it maintains a shape near to the sinusoid. The stator current is quickly stabilized without overtaking. The speed responds without overtaking to the torque variations, the trajectory of the field extremity is practically circular, and its amplitude is constant.



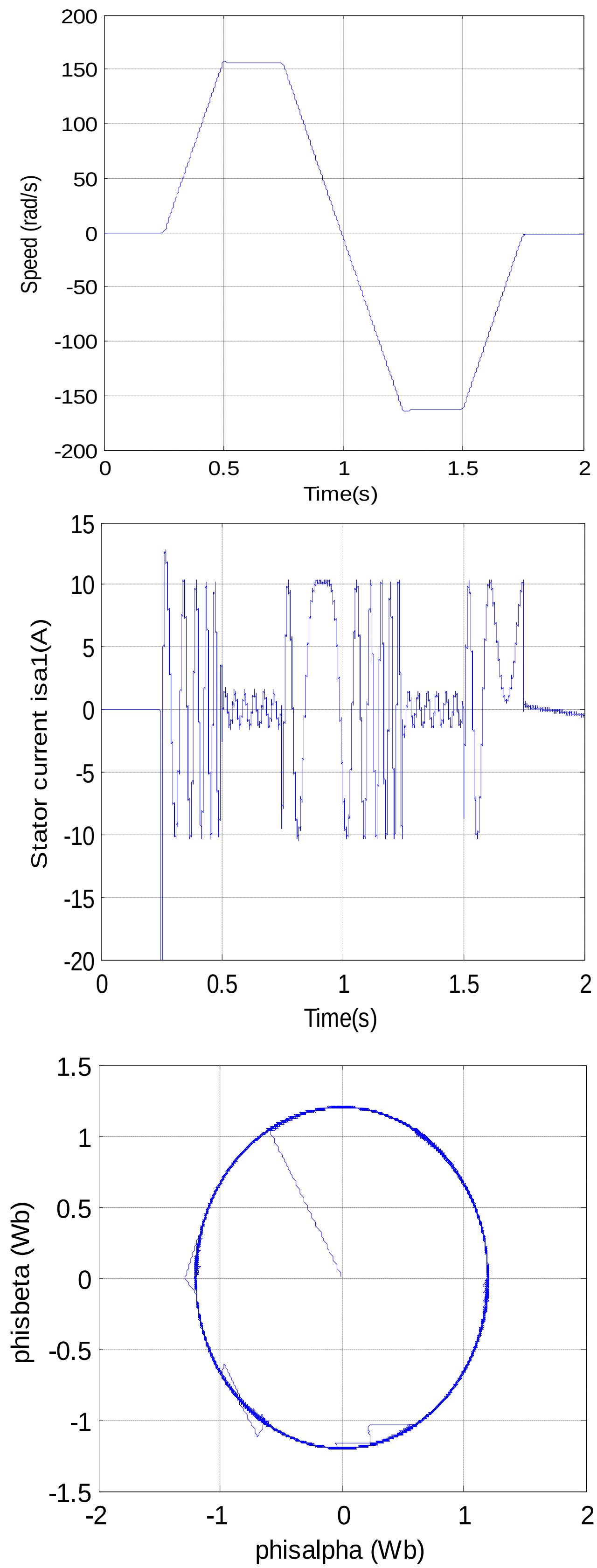
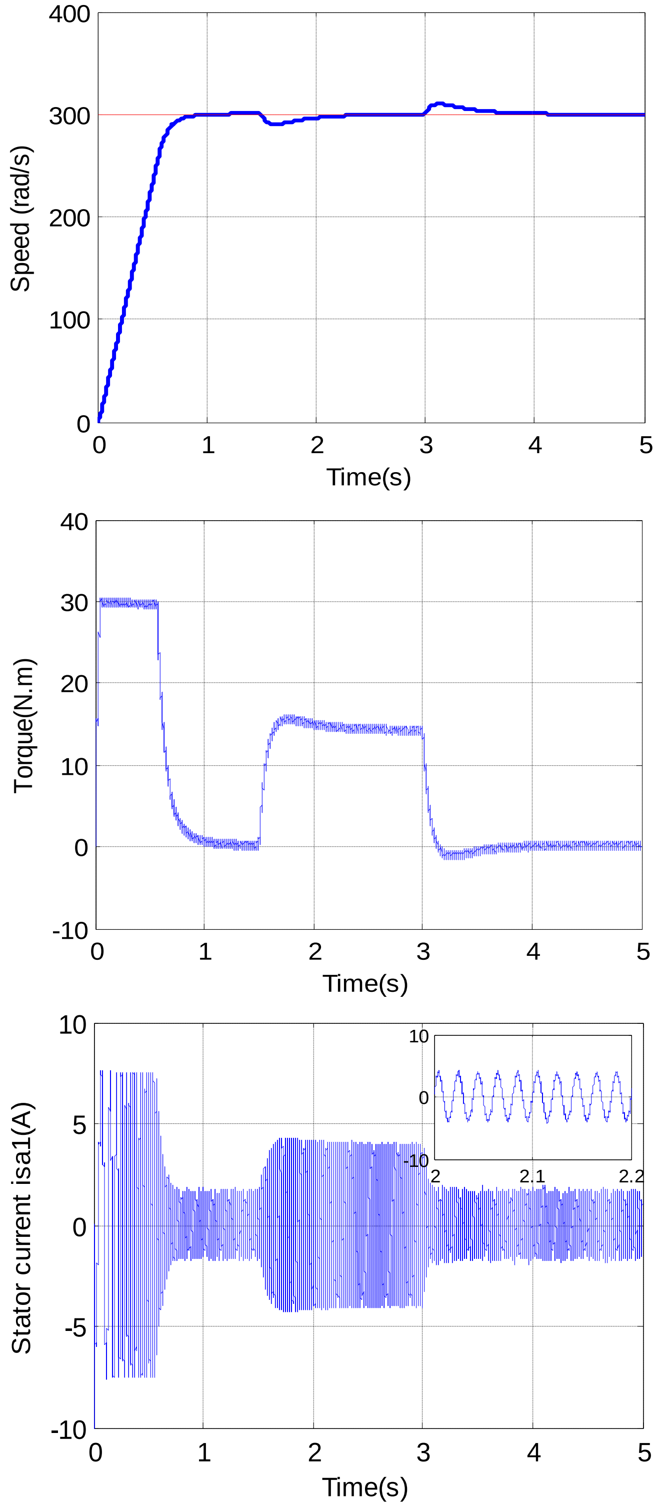


Fig. 6 DTC of SPIM Without speed regulation

We introduce now the regulation loop speed for obtained a reference torque. The simulation results are given in Figure 7.



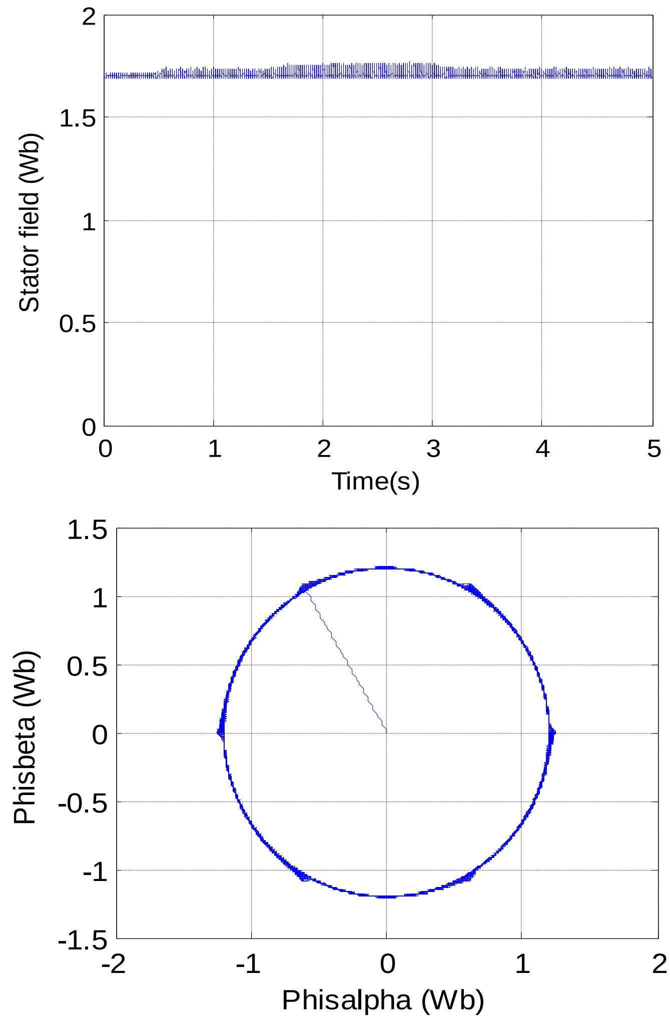


Fig. 7 DTC of SPIM with load torque (14 N.m) between [1.5 3] s

The speed reaches its reference value (300 rad/s) after (1s) without overtaking. The perturbation reject is achieved at (0.8s). At t=1.5s, we applied a load torque (14 N.m), the stator current increase (4.3A) and the machine developed an electromagnetic torque for compensate the load torque, it reaches at starting (30 N.m). The excellent dynamic performance of stator field is evident.

V. ROBUSTNESS TESTS

The robustness of the Direct Torque Control of the SPIM is visualized for two tests: the first is the variation of speed; the second is the load variation.

The simulation results obtained are given in Figure 8

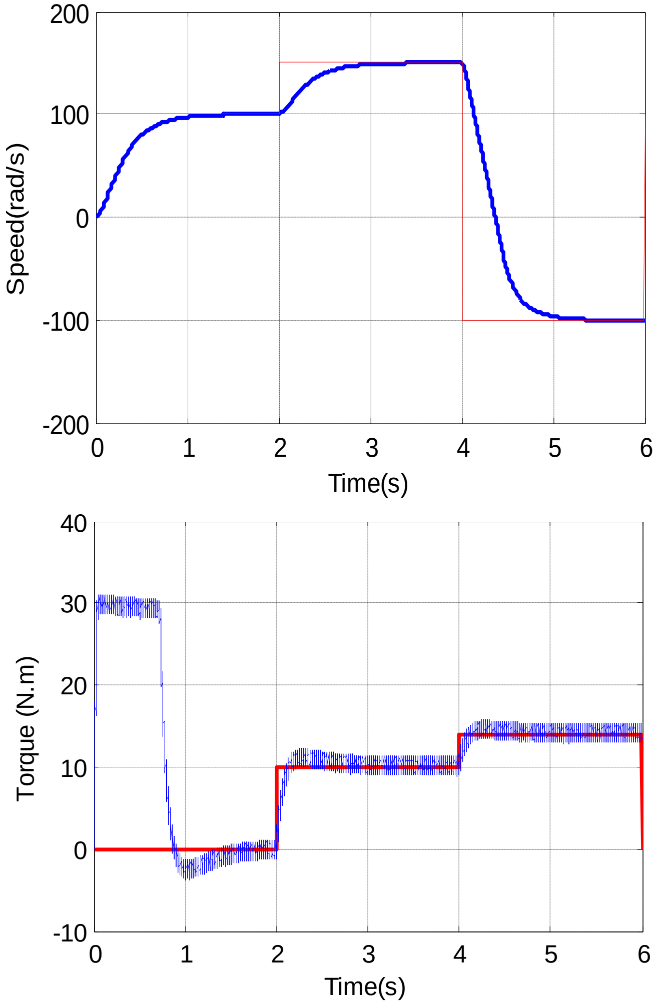


Fig. 8 DTC of SPIM with speed and load variation

The simulation results show that the speed and the torque follow their reference values (wref=100, 200 and -100 rad/s; Tref=0, 10 and 14 N.m) without overtaking. The response of the system is positive, and the DTC proved his robustness.

VI. CONCLUSION

In this paper we are presented a Direct Torque Control (DTC) for a Six Phase Induction Machine (SPIM) drive using a PI regulator. This control scheme allows direct and independent electromagnetic torque and flux control, selecting an optimal switching vector. The simulation results show that the DTC present a good dynamics performances (fast torque and flux response, speed without ouverking,…). The proposed scheme proved his robustness with speed and load variation.

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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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