Direct Torque Control Strategy for Dual Three Phase Induction Motors

A. Belgacem
UR Modélisation, Analyse
et Commande des Systèmes
Route de Médenine 6029,
Gabès , Tunisie

M.A. Fnaiech
UR Modélisation, Analyse
et Commande des Systèmes
Route de Médenine 6029,
Gabès , Tunisie

M.N. Abdelkrim
UR Modélisation, Analyse
et Commande des Systèmes
Route de Médenine 6029,
Gabès , Tunisie

ABSTRACT

In this paper, a comparison between a classic direct torque control (DTC) and a modified (DTC) of a dual three phase induction machine (SPIM) will be introduced. In this work, the SPIM has a dual three phase windings spatially shifted by θ electrical degree wich is equal to 60°. SPIM drive has 64 inverter switching states which provide higher possibility in selecting space voltage vectors than three phase induction machines. The performances of those two control schemes are evaluated and compared by simulation in terms of flux and torque.

General Terms:

Induction machines, Control of systems

Keywords:

Dual three phase induction machines, direct torque control.

1. INTRODUCTION

In the high and small power applications, the multi phase induction machines are frequently used. In fact it's improving a high reliability and fault tolerance. That's why in industrial applications the dual phase induction machine (SPIM) is probably the most popular. The first paper on a dynamic model of the six-phase induction machine (SPIM) was published in 1980 [1].
In the multiphase drive systems, the electric machine has more than three phases in the stator and the same numbers of inverter legs are in the inverter side. In comparison with three phases IM drives, SPIM drives are supplied with a 6 phase inverter.

The direct torque control (DTC) was initially proposed by Takahashi in 1986 [2] and Depenbrock [3].In these last decades, this method of controlling becomes a powerful control method for motor drives. The Direct Torque Control (DTC) method is characterized by its simple implementation and a fast dynamic torque response [4]. It provides a fast torque response and also is robust against machine parameter variations [4]. The direct torque control uses a hysteresis comparators to control the stator flux and electric torque . The total number of the six-phase inverter switch combinations is $2^6 = 64$, so there are 64 space voltage vectors .
In this paper a modification of the switching table is presented and it is compared to the classic DTC. The present paper is organized as follows: Section 2 is reserved to describe the model of dual three phase multi-phase drive systems. A presentation of the DTC of dual three phase induction machines is given in section 3. In section 4, a modified control table for DTC of SPIM is introduced. In section 5, numerical simulation are presented where a comparison between the two approaches is included. This paper will be closed by the main concluding remarks .

2. MODEL OF SPIM

The basic equations of SPIM are given in [5] and [6]. the SPIM can be decomposed into three two-dimensional orthogonal subspaces $(\alpha, \beta), (o_1, o_2), (o_3, o_4)$ by applying the following transformation matrix $[T_6]$ [5].

$$[T_6] = \begin{bmatrix} 1 & \cos(\theta) & -\frac{1}{2} & \cos(\frac{2\pi}{3}+\theta) & -\frac{1}{2} & \cos(\frac{4\pi}{3}+\theta) \\ 0 & \sin(\theta) & \frac{\sqrt{3}}{2} & \sin(\frac{2\pi}{3}+\theta) & -\frac{\sqrt{3}}{2} & \sin(\frac{4\pi}{3}+\theta) \\ 1 & \cos(\pi-\theta) & -\frac{1}{2} & \cos(\frac{\pi}{3}-\theta) & -\frac{1}{2} & \cos(\frac{5\pi}{3}-\theta) \\ 0 & \sin(\pi-\theta) & -\frac{\sqrt{3}}{2} & \sin(\frac{\pi}{3}-\theta) & \frac{\sqrt{3}}{2} & \sin(\frac{5\pi}{3}-\theta) \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix} \tag{1}$$

with θ (60 electrical degrees) is the electrical angle between the two three phase windings the equations of the stator and rotor voltage by the decouples SPIM model are as follow :
α-β **subspace**

$$\left\{ \begin{array}{c} v_{s\alpha} = R_s i_{s\alpha} + L_s \frac{di_{s\alpha}}{dt} + M \frac{di_{r\alpha}}{dt} \\ v_{s\beta} = R_s i_{s\beta} + L_s \frac{di_{s\beta}}{dt} + M \frac{di_{r\beta}}{dt} \\ 0 = R_r i_{r\alpha} + L_r \frac{di_{r\alpha}}{dt} + \omega_r L_r i_{r\beta} + M \frac{di_{s\alpha}}{dt} + \omega_r M i_{s\beta} \\ 0 = R_r i_{r\beta} + L_r \frac{di_{r\beta}}{dt} - \omega_r L_r i_{r\alpha} + M \frac{di_{s\beta}}{dt} - \omega_r M i_{s\alpha} \end{array} \right. \tag{2}$$

The stator and rotor flux linkages of this subspace are:

$$\left\{ \begin{array}{l} \psi_s = L_s i_s + M i_r \\ \psi_r = L_r i_r + M i_s \end{array} \right. \tag{3}$$

with:

$$\left\{ \begin{array}{c} M = L_{ms} \\ L_s = L_{ls} + M \\ L_r = L_{lr} + M \end{array} \right.$$

Where $R_s, R_r, L_s, L_r, L_{ms}$ and M represent the parameters of the system.
o_1-o_2 **subspace**

$$\left\{ \begin{array}{l} v_{so_1} = R_s i_{so_1} + L_{ls} \frac{di_{so_1}}{dt} \\ v_{so_2} = R_s i_{so_2} + L_{ls} \frac{di_{so_2}}{dt} \end{array} \right. \tag{4}$$

o_3-o_4 subspace

$$\begin{cases} v_{so_3} = R_s i_{so_3} + L_{ls}\frac{di_{so_3}}{dt} \\ v_{so_4} = R_s i_{so_4} + L_{ls}\frac{di_{so_4}}{dt} \end{cases} \tag{5}$$

the electromechanical energy conversion is in the α-β subsystem. The o1-o2 and o3-o4 subsystems are only producing losses.

3. DTC METHOD OF SPIM

The main idea of the DTC method is that in each sampling period the stator flux and torque stay in their hysteresis bands by proper selection of the stator space voltage vectors .
The stator flux linkage for every sampling period can be written as follow:

$$\begin{cases} \psi_{s\alpha} = \int\limits_0^t (v_{s\alpha} - R_s i_{s\alpha})dt \\ \psi_{s\beta} = \int\limits_0^t (v_{s\beta} - R_s i_{s\beta})dt \end{cases} \tag{6}$$

Thus the stator flux can be controlled by the proper selection of the space voltage vector.
The torque can be expressed as follow:

$$\Gamma_m = p(\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}) \tag{7}$$

Therefore, stator flux and torque of SPIM can be controlled simultaneously.
Each phase switching function wich is called $(\mathrm{Sa}, \mathrm{Sb}, \mathrm{Sc}, \mathrm{Sa}', \mathrm{Sb}', \mathrm{Sc}')$ can take 1 or 0 value all based on the state of the upper or lower switches of the inventer. The switching function assumes a value of 1 or 0 depending on the position of the upper switch . If it is 'on' then the value is 1 otherwise it is 0 . A number of 64 switching modes can be had by combinational analysis of all states of 12 inverter legs. The $\alpha{-}\beta$, ol-o2 and o3-o4 subspaces are where the 64 voltage vectors are projected .
the $\alpha{-}\beta$, ol-o2 and o3-o4 subspaces are where the figures (2 ,3 and 4) are showed. the decimal numbers show the switching mods of the inverter legs.

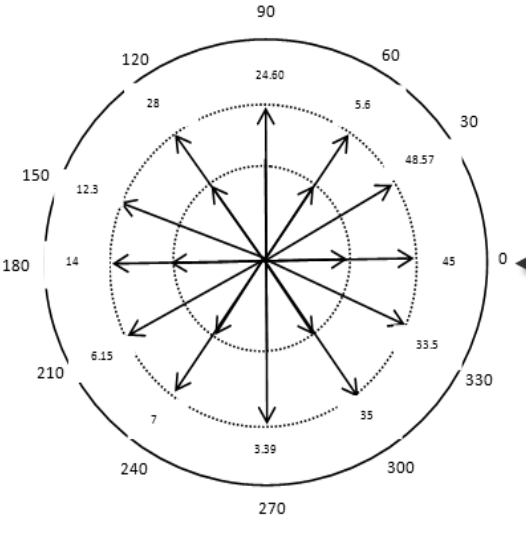

Fig. 1. Voltage vectors on the $\alpha - \beta$ plane .

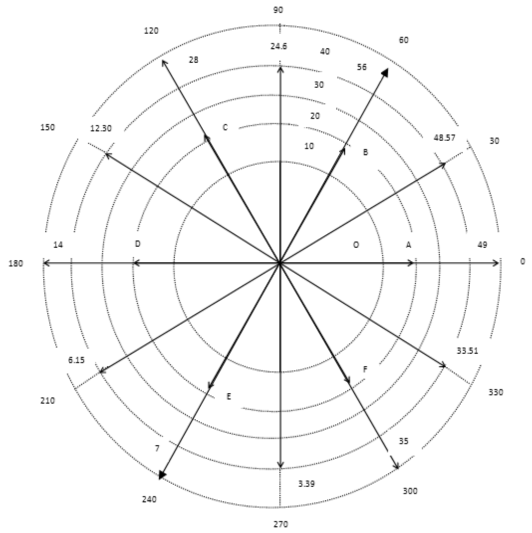

Fig. 2. Voltage vectors on the o1-o2 plane .

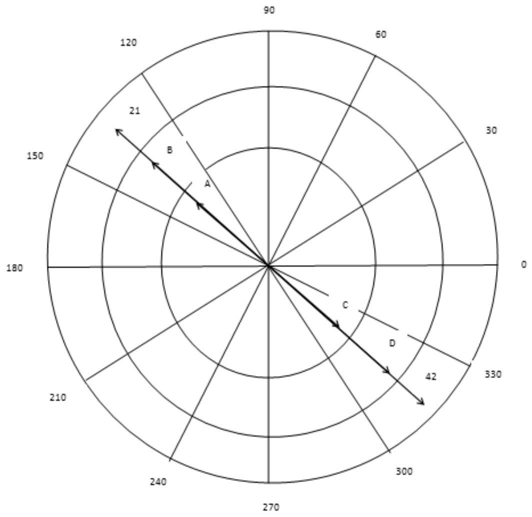

Fig. 3. Voltage vectors on the o3-o4 plane .

In order to maximize the amplitude of (α,β) voltage vectors and to minimize (o1-o2) and (o3-o4) voltage vectors we choose the switching modes for the SPIM . Thats why we choose this combination 49,56,28,14,7 and 35. Clearly these switching modes generate zero voltage vectors on (o1,o2) subspace (Fig.3) and non zero voltage vectors on (o3,o4) subspace (Fig.4) . To maintain the torque and the stator flux within the limits of flux and torque hysteresis bands the selection of voltage vector is made (according to the principal of DTC) . The voltage vectors are selected according to the errors of stator flux, torque and θ the angular position of the stator vector flux.
The stator flux angle and amplitude are as follow:

$$\begin{cases} \theta = \tan^{-1}(\frac{\psi_{s\beta}}{\psi_{s\alpha}}) \\ \psi_s = \sqrt{{\psi_{s\alpha}}^2 + {\psi_{s\beta}}^2} \end{cases} \tag{8}$$

The table 1 shows the selection of the stator flux vectors :

Table 1. Vectors in DTC for SPIM.

Sectors		1	2	3	4	5	6
$u_\psi = 1$	$u_{te} = 1$	V56	V28	V14	V7	V35	V49
	$u_{te} = 0$	V63	V63	V63	V63	V63	V63
	$u_{te} = -1$	V35	V49	V56	V28	V14	V7
$u_\psi = 0$	$u_{te} = 1$	V28	V14	V7	V35	V49	V56
	$u_{te} = 0$	V0	V0	V0	V0	V0	V0
	$u_{te} = -1$	V7	V35	V49	V56	V28	V14

3.1 IMPROVEMENT OF THE SWITCHING TABLE

The idea was inspired by the zone shift strategy applied to the three phase induction machine [7] [8]. The goal is to ameliorate the classical DTC by a change of the table 1 and modify the six zones of the classical DTC .For exemple, instead of taking the first sector $-\frac{\pi}{6} \leq \theta \leq \frac{\pi}{6}$, it's taken $0 \leq \theta \leq \frac{\pi}{3}$ [9] [10] . The figures 5 and 6 show the difference between the two strategies

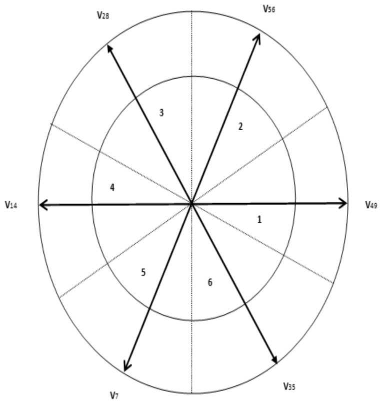

Fig. 4. Six sectors of classical DTC .

The table 2 shows the selection of the stator flux vectorsfor the modified DTC

3.2 Simulation results

To compare the performance of the two DTC methods , we have developed a program in MATLAB Simulink. Equations (8) have been used to estimate the amplitude and angle of stator flux vector. We have used a two level hysteresis regulators for controlling stator flux and a three level hysterisis comparator for the electromagnetic torque. The sampling period is fixed at $50\mu s$. The parameters of the simulated rotor are given in the table 3.

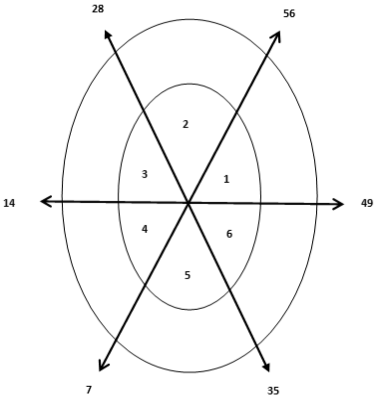

Fig. 5. Modified DTC and its six sectors .

Table 2. Vectors vectors in DTC for SPIM.

Sectors		1	2	3	4	5	6
$u_\psi = 1$	$u_{te} = 1$	V56	V28	V14	V7	V35	V49
	$u_{te} = 0$	V63	V63	V63	V63	V63	V63
	$u_{te} = -1$	V49	V56	V28	V14	V7	V35
$u_\psi = 0$	$u_{te} = 1$	V14	V7	V35	V49	V56	V28
	$u_{te} = 0$	V0	V0	V0	V0	V0	V0
	$u_{te} = -1$	V7	V35	V49	V56	V28	V14

Table 3. Induction Machine Parameters.

Rated power	0.3 Nm
Number of poles	2
Stator resistance	1.04Ω
Rotor resistance	0.64Ω
Friction coefficient	$2 \times 10^{-4} kg.m^2/s$
Inertia	$9.5 \times 10^{-5} kg.m^2$

Fig. 7 and Fig. 8 present the evolutions of the stator flux and the electromagnetic torque for performance in terms of convergence of these parameters to there reference values. fig 9 shows the quadrate component of stator flux versus horizontal component of stator flux in the stationary reference frame. After some transient, the stator flux locus becomes a circle. As it shows amplitude of stator flux remains almost constant in the command value.
Compared to previous results (Figures 7 and 8), the results, illustrated by figures 10 and 11, clearly show better performance. Figure 10 shows that the flux of the Modified DTC offers the fast transient responses That means the trajectory of stator flux established more quickly than that of the classic DTC. The simulation results (fig 12) confirm that the Modified DTC presents the advanced performance to achieve tracking of the desired smooth circular trajectory of stator flux locus.

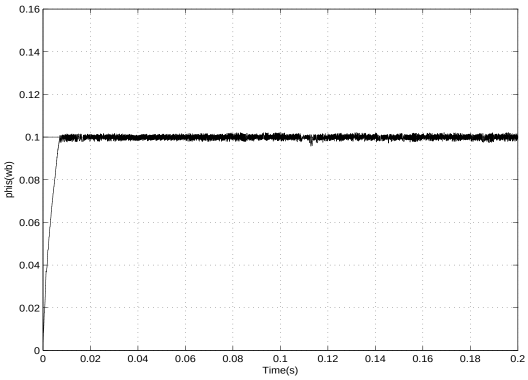

Fig. 6.   Stator flux for classic DTC

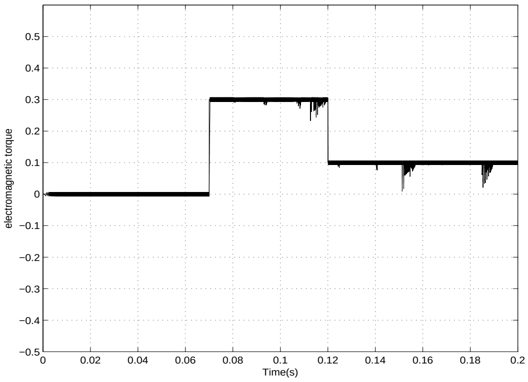

Fig. 7.   Electromagnetic Torque for classic DTC

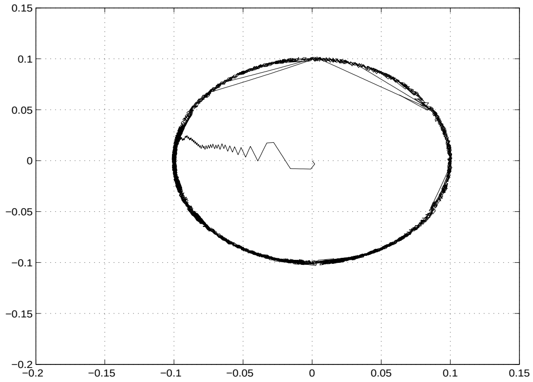

Fig. 8.   Stator flux for classic DTC

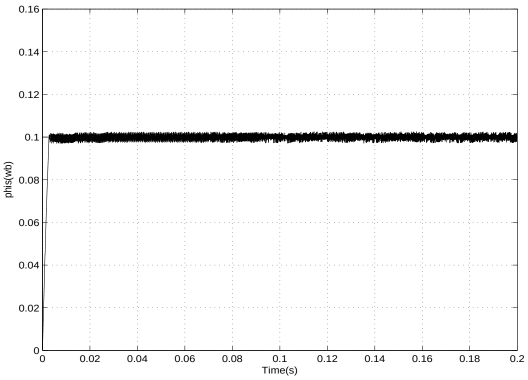

Fig. 9.   Stator flux for modified DTC

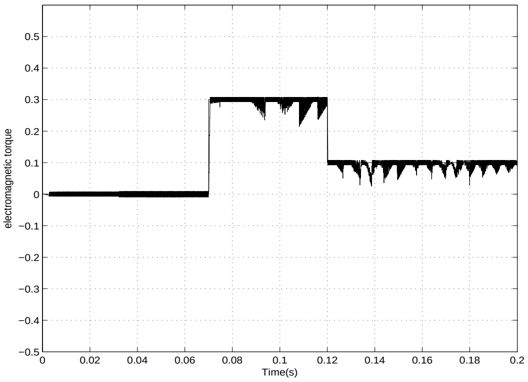

Fig. 10.   Stator flux for modified DTC

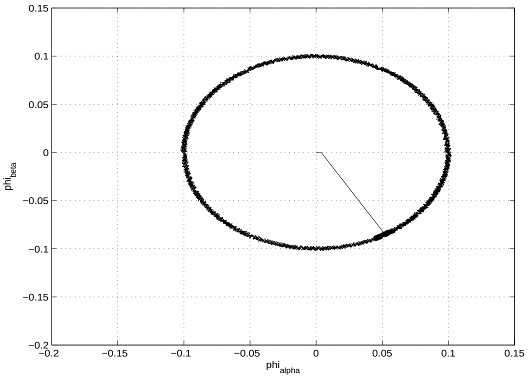

Fig. 11.   Electromagnetic Torque for modified DTC

4. CONCLUSION

This paper has presented a contribution for a comparison between the classic DTC and a modified DTC for dual three phase induction machine. the performances of those various methodologies are evaluated and compared by simulation in terms of response time. The obtained results of the modified DTC shows satisfactory results.

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