COMPARATIVE EXPERIMENTAL STUDY OF THREE SWITCHING TABLES OF A DTC APPLIED TO AN INDUCTION MOTOR FOR A TRACKING SYSTEM

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Abstract: *The direct torque control (DTC) of an induction motor (IM) has been the subject of several studies and developments since the eighties. Efforts have been made continuously to improve the performance of this control technique to make it more efficient and robust for industrial applications that have also experienced a remarkable development. It cites, among these applications, the tracking system, which was the subject of much research. This study provides experimental validation of the algorithms developed in this topic, and help for implementation of a simple DTC, to apply it to the tracking system, proposed by the authors. The interest of this study is that it is based on the choice of switching tables (ST) and therefore on algorithms and not on the hardware part, which is expensive. The tests were carried out under the same conditions with the same equipment of the testbed, to get a good comparative study. Three variants were tested: simple ST, table of sectors shifted by 30 ° and a table with 12 sectors. The results show an improvement, but a dilemma between the torque ripple and those of the stator flux.*

Key words: *DTC, IM, ST, Torque and Flux Ripples.*

1. Introduction

The induction motor (*IM*) has several advantages over other types of electric motors. The recent development of the technology of power electronics has put in competition a few other types of motors, which had difficulty of design in the past, such as the permanent magnet synchronous motor, for example. But probably, it will stay, for next years, the most dominant motor in industrial applications, because of its techno-economic characteristics [1-7].

Its association with a static inverter constitutes a variable speed transmission of which the industrial use or general public does not cease growing.

Several work thus led to the implementation of the techniques of control for the *IM*. A diagram of control based on the transitory or dynamic model of the machine which is the vectorial control of the motor has been developed. This type of control makes it possible to have a faster dynamics of response and a better precision of the control of the torque.

DTC was introduced between 1984 and 1985 by *Depenbrock* and *Takahashi* especially for the asynchronous machines [1-4]. The main advantages of *DTC* are the simplicity of the control scheme and its unresponsiveness to parameters variations (except stator resistor), [8].

In the conventional *DTC*, the employment of the hysteresis controllers, in order to regulate the stator magnetic flux and torque, have by nature high torque ripples and variable switching frequency depending on speed, load torque and hysteresis bands. This leads to a difficulty to control torque and flux at a very low speed [1-9].

*Lascu, C.et al.*in [10], have presented a modified *DTC* using (*SVM*) for an *IM* with fixed switching frequency and low ripple for torque and flux. This system requires two proportional-integral (*PI*) controllers properly tuned at the same time for the best performance.

Martins, C. et al in [11] and *Cirrincione, M., et al.* in [12] have proposed solutions to reduce the torque ripples, this strategy relies on increasing the number of vectors applied voltage, which can improve the ripples band.

The MI which is powered by a three-level inverter has the same dynamic performance as those obtained with a two-level inverter with low torque and flux ripples, but this increases the cost of implantation, due to the cost of the three-level inverter and also the *ST* becomes large.

The aim of this study is to have a simple and less expensive system, to apply it to a tracking system which was proposed by [6], and can be used for thermal system or photovoltaic; this requires that it focuses on improvements, software side only.

For this, we must keep the same equipment of testbed and the same control conditions (gains of *PI*, reference values, hysteresis comparators), and therefore, only the *ST* must be changed.

The experimental study examines a *DTC* applied to an *IM* for three different switching tables: simple ST, table with sectors shifted by 30° and table with 12 sectors in order to reduce the ripples of the electromagnetic torque and flux.

2. IM model

The stator and rotor flux equations of *IM* can be written in the reference frame of *Park* in the following form [6]:

$$\dot{X} = AX + BU \qquad (1)$$

Such as:

$$X = \left[i_{\alpha s}\ i_{\beta s} \phi_{\alpha s}\ \phi_{\beta s}\right]^t \ , U = \left[v_{\alpha s}\ v_{\beta s}\right]^t$$

$$A = \begin{bmatrix} -\frac{1}{\sigma}\left(\frac{1}{T_r}+\frac{1}{T_s}\right) & -\omega_r & \frac{1}{\sigma L_s T_r} & \frac{\omega_r}{\sigma L_s} \\ \omega_r & -\frac{1}{\sigma}\left(\frac{1}{T_r}+\frac{1}{T_s}\right) & -\frac{\omega_r}{\sigma L_s} & \frac{1}{\sigma L_s T_r} \\ -r_s & 0 & 0 & 0 \\ 0 & -r_s & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 1 & 0 \\ 0 & 1 \end{bmatrix}, \sigma = 1 - \frac{m^2}{L_s L_r}, T_s = \frac{L_s}{r_s}, T_r = \frac{Lr}{r_r},$$

where, rotor speed is given by: $\omega_r = p\Omega$

In addition, the electromagnetic torque can be expressed by:

$$T_e = \frac{3}{2} p(\phi_{\alpha s} i_{\beta s} - \phi_{\beta s} i_{\alpha s}) \qquad (2)$$

The mechanical equation of the *IM* can be expressed as flows:

$$J\,\dot{\Omega} = T_e - T_r - f_r \Omega \qquad (3)$$

3. Conventional DTC

The *DTC*, as shown in figure 1, consists of directly controlling the inverter switches turn OFF or ON, on the calculated values of the stator flux and torque from relations (5) and (6). The variations in the switches state involve the variations in electromagnetic state motor.

They are no longer controlled on the basis of voltage and frequency references given to the commutation control of a pulse width voltage modulation inverter [1-9].

The reference frame related to the stator, makes possible to estimate flux and torque on the one hand and the position of flux stator on the other hand.

The aim of the switches control is to give the vector representing the stator flux the direction determined by the reference value [6].

The two stator flux component are given by:

$$\begin{cases} \phi_{s\alpha} = \int_0^t (v_{s\alpha} - r_s I_{s\alpha})\, dt \\ \phi_{s\beta} = \int_0^t (v_{s\beta} - r_s I_{s\beta})\, dt \end{cases} \qquad (4)$$

The *DTC* is deduced from the two approximations described by the formulas (5) and (6) if the Ohmic drop of the stator is neglected in (4) [6]:

$$\bar{\phi}_s(k+1) \approx \bar{\phi}_s(k) + \bar{V}_s T_E \quad \rightarrow \quad \Delta\bar{\phi}_s \approx \bar{V}_s T_E \qquad (5)$$

$$T_e = k\,(\bar{\phi}_s + \bar{\phi}_r^{'}) = k\,\left|\bar{\phi}_s\right|\left|\bar{\phi}_r^{'}\right| \sin(\delta) \qquad (6)$$

with

$$\begin{cases} \hat{\phi}_s = \sqrt{\hat{\phi}_{s\alpha}^2 + \hat{\phi}_{s\beta}^2} \\ \angle\hat{\phi}_s = arctg \dfrac{\hat{\phi}_{s\beta}}{\hat{\phi}_{s\alpha}} \end{cases} \qquad (7)$$

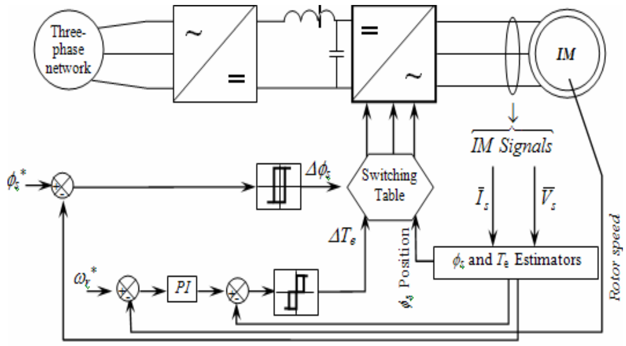

Fig.1. Block Diagram of a Classical *DTC*

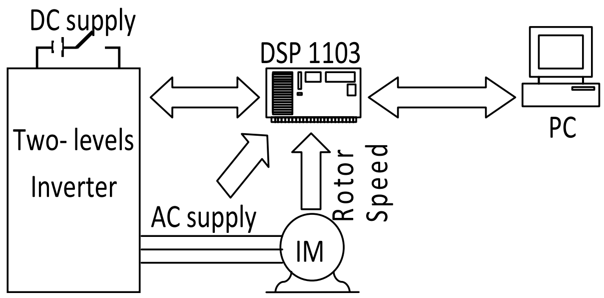

Fig.2. Diagram of an implementation of a *DTC* applied to the *IM*.

A two levels classical voltage inverter can achieve seven separate positions in the phase corresponding to the eight sequences of the voltage inverter [1], [6]. These positions are illustrated in figure 3. In addition, Tables 1 and 2 show the sequences for each position.

Furthermore, Tables 4 and 5 have the sequences corresponding to the position of the stator flux vector in different sectors for the others strategies of *ST* (see figures 5 and 6).

The flux and torque are controlled by two comparators with hysteresis illustrated in figure 4. The dynamics torque, are generally faster than the flux. So, a comparator hysteresis of several levels is, justified to adjust the torque and minimize the switching frequency average [6].

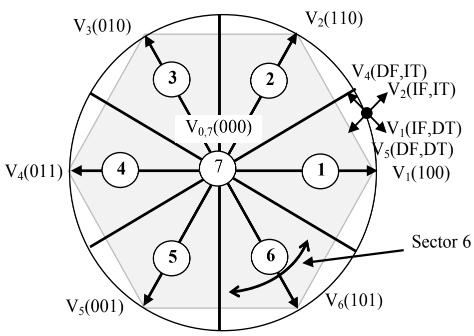

Fig.3. Different vectors of stator voltages provided by a two levels inverter.

where

I(**D**)**F** : **I**ncrease (**D**ecrease) of **F**lux amplitude.

I(**D**)**T** : **I**ncrease (**D**ecrease) of **T**orque.

Table 1. Table generalized of voltage vectors generated by a classical *DTC*.

	Increase ↑	Decrease ↓
ϕ_s	V_{k-1} ,V_k and V_{k+1}	V_{k-2} ,V_{k+2} and V_{k+3}
T_e	V_{k+1} and V_{k+2}	V_{k-1} and V_{k-2}

Table 2. ST for a classical *DTC*.

$\Delta\phi_s$	ΔT_e	S_1	S_2	S_3	S_4	S_5	S_6
1	1	110	010	011	001	101	100
	0	000	000	000	000	000	000
	-1	101	100	110	010	011	001
0	1	010	011	001	101	100	110
	0	000	000	000	000	000	000
	-1	001	101	100	110	010	011

Where, $S_{i=1...,6}$ are localization sectors of the stator vector flux.

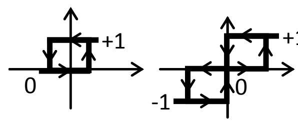

Fig.4. Hysteresis comparators used to regulate flux and torque.

4. DTC with sectors shifted by 30°

The same principle of basic *DTC* control of the *IM,* which is supplied by a two-level inverter, is applied for the other *ST*.

All sectors are shifted by an angle of 30° leading to an angle of the first sector between 0° and 60° as shown in figure 5.

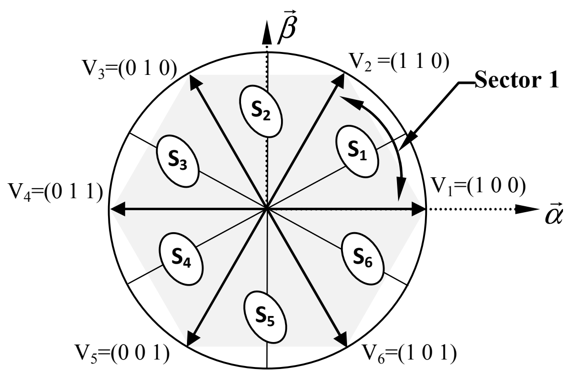

Fig.5. Different vectors of stator voltages, in case of table with sectors shifted by 30°.

The difference between a *DTC* with a simple ST and that with sectors shifted is summarized in table 3.

Table 3. Comparison between the simple table and the table with sectors shifted by 30°.

	Simple Table	Sectors shifted by 30°
V_1	-30° → 30° torque undetermined	-60° → 0° DT , IF
V_2	30° → 90° IT , IF	0° → 60° IT , IF
V_3	90° → 150° IT , DF	60° → 120° flux undetermined
V_4	150° → 210° torque undetermined	120° → 180° IT , DF
V_5	210° → 270° DT , DF	180° → 240° DT , DF
V_6	270° → 330° DC , IF	240° → 300° flux undetermined

Table 4 presents the ST when the sectors are shifted by 30°. We can see the difference from the classical *DTC* in the third and the fourth lines for Table 2.

Table 4. ST of DTC with shifting 30°

$\Delta\phi_s$	ΔT_e	S_1	S_2	S_3	S_4	S_5	S_6
1	**1**	110	010	011	001	101	100
	0	000	000	000	000	000	000
	-1	100	110	010	011	001	101
0	**1**	011	001	101	100	110	010
	0	000	000	000	000	000	000
	-1	001	101	100	110	010	011

5. DTC with 12 sectors

The 12 sectors method uses the same block diagram as shown in figure 3; but the ST now consists of 12 non null voltage vectors, to be selected.

The flux angle now lies on one of the 12 sectors as shown in figure 6.

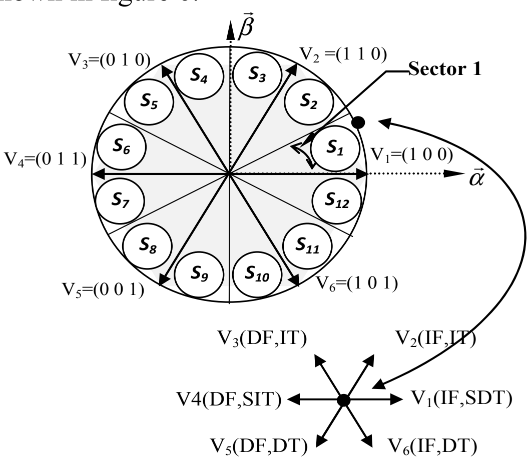

Fig.6. Different vectors of stator voltages in case of table with 12 sectors.

with:

SI(D)T : **S**mall **I**ncrease (**D**ecrease) of **T**orque.

The switching logic is similar to that of a conventional *DTC* [13].

Table 5 shows the strategy for the first sector and the 12 sector where we can deduce the rests of all sectors.

Table 5. ST of *DTC* with 12 sectors

		S_1	S_{12}
Flux	Increase	V_1 ,V_2 and V_6	V_1 ,V_2 and V_6
	Decrease	V_3 ,V_4 and V_5	V_3 ,V_4 and V_5
Torque	Increase	V_2 ,V_3 and V_4	V_1 ,V_2 and V_3
	Decrease	V_5 ,V_6 and V_1	V_4 ,V_5 and V_6

6. DTC experimental results

The parameters of the *IM* used in this study and the description of the testbed are given at the end of this paper. For a comparison study, the results are grouped into sets of three.

In Figure 7, the rotor speed reaches its reference with a gap of about 4rad / s for the simple table and the table of 12 sectors, the reference of this speed is 100 rad / s. this difference is due to the load which is 15 N.m. In the same test conditions, the rotor speed drops by about 2 rad / s in the case of sectors shifted by 30 ° compared to the other tables, but it may be noted that fluctuations in speed, are less present in the latter strategy compared to the other two strategies.

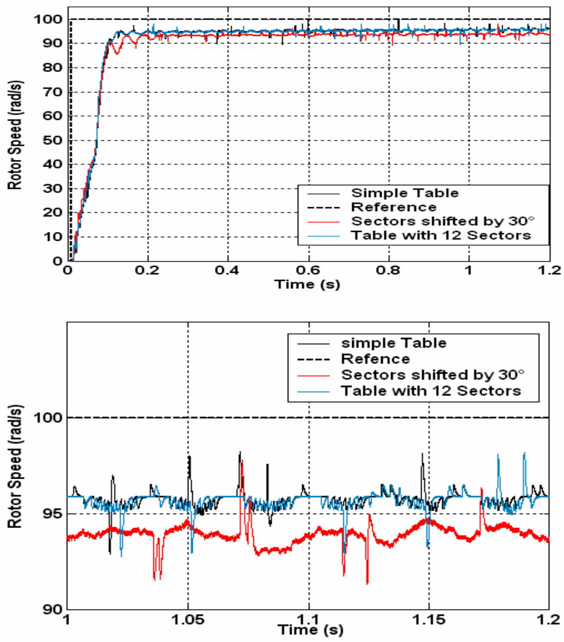

Fig.7. Rotor Speed, for all strategies of *DTC*.

The torque has been improved in the last two strategies (Figure 8), but even if it was characterized by annoying fluctuations.

The case of sectors shifted by 30° presents the most remarkable improvement.

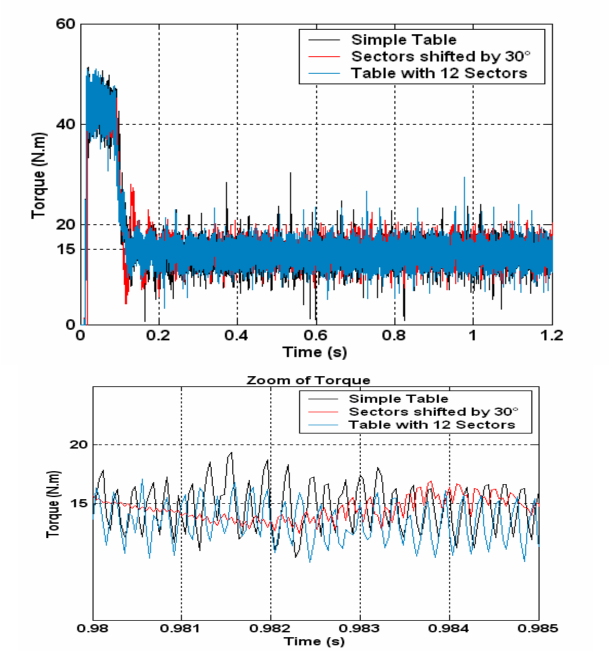

Fig.8. Torque developed, for all strategies of *DTC*.

Figure 9 shows the reason why the conventional and the *DTC* with 12 sectors are not so different, which is confirmed by [13]. *DTC* with sectors shifted by 30° is well characterized by a different PWM, which gives better improvement in terms of ripples.

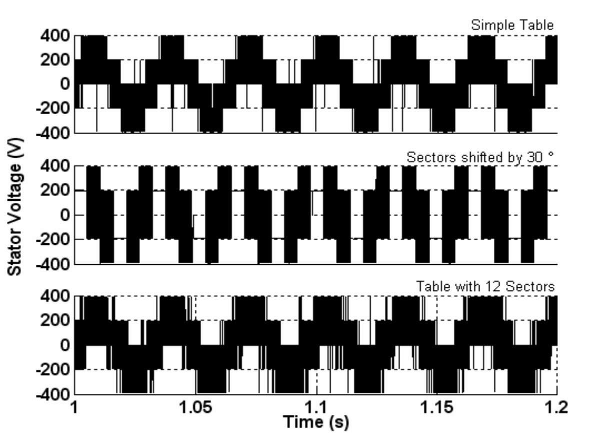

Fig.9. Voltage of a stator phase, for all strategies.

In figures 10 and 11, the stator flux has fewer ripples in the case of conventional DTC than the other strategies.

This case presents a dilemma for choice between ripples of torque and ripples of flux.

The flux rotation frequency, in the case of sectors shifted by 30 ° is bigger than that of other tables; therefore the flux performs well in these two tables than in the table with sectors shifted, this can interpret the ripples of stator flux.

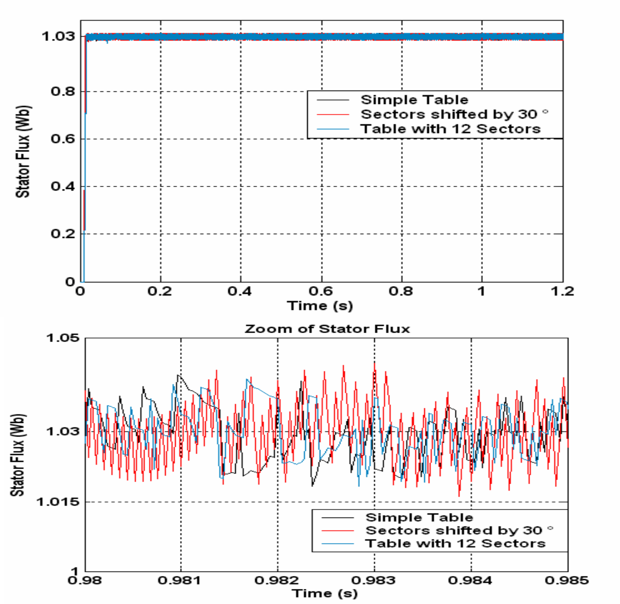

Fig.10. Stator flux, for all strategies of DTC.

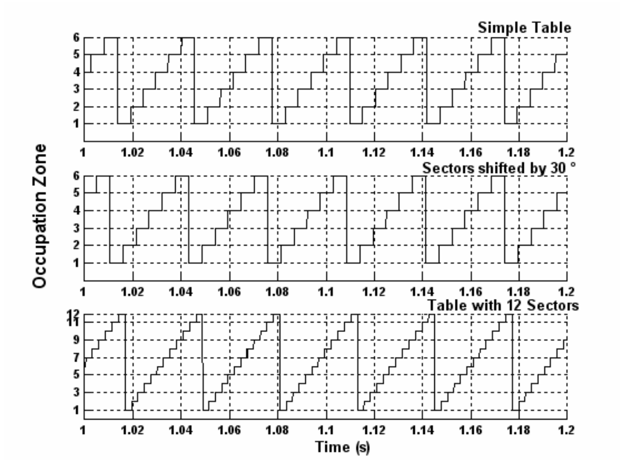

Fig.11. Occupation zones, for all strategies.

7. Conclusion

In this experimental study, we chose three different strategies of DTC that are presented by three different ST in order to validate the control algorithms developed in [6] and choose, so the best strategy that fits for the implementation of a tracking system.

From the experimental obtained results, the DTC with sectors shifted by 30°, can improve the torque ripple but not those of the flux, which is interesting for the application in issue (tracking).

DTC with 12 sectors can also improve the control slightly, confirming the results of [13], but reported less interest since it employs a ST large enough compared to other strategies.

This experimental study helps us to adopt the best simple ST, for the implementation of a simple DTC to apply it, to a tracking system designed for solar system (thermal or photovoltaic).

Description of the testbed (figure 12)

1-IM (See Table 6 for parameters)
2-The load (PMSG)
3-PC: P3 (X86 Family 6, Model 8, stepping 6), 866 MHz, 256 MO (Ram), VGA: Matrox Millinium G450 Dual head (32 MO), OS: Windows 2000 pro.
4-DSPACE: ISA, DSP 1103 PPC Controlled Board.
5-INVERTER: Two levels (max 100 KHz), IGBT (1200V-50A).
6-SENSORS:
a: Speed: Universal DIGISINE, DHO5 [BEI-IDEACOD],
b: Current: AM30N 10-100A/1V,
(Input: 100A peak max, DC. 100kHz|output:100-10mV/A, 1V peak max.
c: Voltage: Differential DP1000 with two outputs 10-100

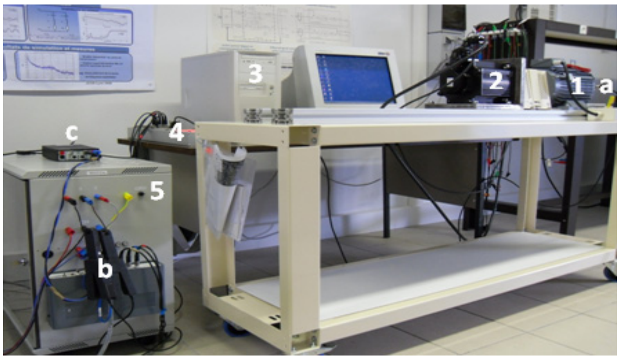

Fig.12. Testbed used in the present study.

Table 6. *IM* parameters used in this study

Pole pairs p	2
Rated power kW (at 50 Hz)	4
Rated voltage (V)	220/380
Stator resistance R_s (Ω)	1.30
Rotor resistance R_r (Ω)	0.91
Self-inductance (stator & rotor) $L_{s,r}$ *(H)*	0.19
Mutual inductance M *(H)*	0.18
J(kg.m²)	0.009
f_r (N.m.s/rad)	0.03

Acknowledgments

This experimental study was conducted within the IREENA laboratory in St Nazaire, University of Nantes. The IREENA's team members find here our appreciation and acknowledgment.

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