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.

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]:

\[ \dot{X} = AX + BU \]  

Such as:

\[ X = \begin{bmatrix} i_{sa} & i_{sb} & \phi_{sa} & \phi_{sb} \end{bmatrix}^T, \quad U = \begin{bmatrix} v_{sa} & v_{sb} \end{bmatrix}^T \]

\[ A = \begin{bmatrix} \frac{1}{\sigma} & \frac{1}{T_r} & -\omega_r & \frac{1}{\alpha L_r T_r} \\ \omega_r & -\frac{1}{\sigma} & \frac{1}{\alpha L_r T_r} & \frac{1}{\alpha L_r T_r} \\ -r_s & 0 & 0 & 0 \\ 0 & -r_s & 0 & 0 \end{bmatrix} \]

\[ B = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\alpha L_r L_s} \\ \frac{1}{\sigma L_s} & 0 \\ 0 & 1 \end{bmatrix} \cdot \sigma = \frac{m^2}{L_r L_s} \]

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

In addition, the electromagnetic torque can be expressed by:

\[ T_e = \frac{3}{2} p(\phi_{sa} i_{sb} - \phi_{sb} i_{sa}) \]  

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

\[ J \ddot{\Omega} = T_e - T_r - f_r \Omega \]  

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:

\[ \phi_{s\alpha} = \int_0^t (v_{s\alpha} - r_s I_{s\alpha}) \, dt \]

\[ \phi_{s\beta} = \int_0^t (v_{s\beta} - r_s I_{s\beta}) \, dt \]

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]:

\[ \Phi_s(k+1) = \Phi_s(k) + \int_{-T_e}^{T_e} \Phi_s \, dt \rightarrow \Delta \Phi_s = \int_{-T_e}^{T_e} \Phi_s \, dt \]  

\[ T_e = k(\Phi_s + \Phi_r) \]  

with

\[ \dot{\Phi}_s = \sqrt{\frac{\dot{\phi}_{s\alpha}^2}{\phi_{s\alpha}} + \frac{\dot{\phi}_{s\beta}^2}{\phi_{s\beta}}} \]

\[ \angle \dot{\phi}_s = \arctg \frac{\dot{\phi}_{s\beta}}{\dot{\phi}_{s\alpha}} \]  

\[ \dot{\phi}_{s\alpha} \]  

\[ \dot{\phi}_{s\beta} \]
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].

Here:
- \( I(D)F \): Increase (Decrease) of Flux amplitude.
- \( I(D)T \): Increase (Decrease) of Torque.

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

<table>
<thead>
<tr>
<th>( \Delta \phi )</th>
<th>( \Delta T_e )</th>
<th>( S_1 )</th>
<th>( S_2 )</th>
<th>( S_3 )</th>
<th>( S_4 )</th>
<th>( S_5 )</th>
<th>( S_6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>110</td>
<td>010</td>
<td>011</td>
<td>001</td>
<td>101</td>
<td>100</td>
</tr>
<tr>
<td>-1</td>
<td>0</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>010</td>
<td>011</td>
<td>001</td>
<td>101</td>
<td>100</td>
<td>110</td>
</tr>
<tr>
<td>-1</td>
<td>0</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
</tr>
<tr>
<td>-1</td>
<td>001</td>
<td>101</td>
<td>100</td>
<td>110</td>
<td>010</td>
<td>011</td>
<td>001</td>
</tr>
</tbody>
</table>

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

Table 2. ST for a classical DTC.

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

<table>
<thead>
<tr>
<th>Simple Table</th>
<th>Sectors shifted by 30°</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30° → 30° torque undetermined</td>
<td>-60° → 0° DT, IF</td>
</tr>
<tr>
<td>30° → 90° IT, IF</td>
<td>0° → 60° IT, IF</td>
</tr>
<tr>
<td>90° → 150° IT, DF flux undetermined</td>
<td>60° → 120° IT, DF</td>
</tr>
<tr>
<td>150° → 210° torque undetermined</td>
<td>120° → 180° IT, DF</td>
</tr>
<tr>
<td>210° → 270° DT, DF</td>
<td>180° → 240° DT, DF</td>
</tr>
<tr>
<td>270° → 330° DC, IF</td>
<td>240° → 300° flux undetermined</td>
</tr>
</tbody>
</table>

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°

<table>
<thead>
<tr>
<th>∆φ</th>
<th>∆Te</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>110</td>
<td>010</td>
<td>011</td>
<td>001</td>
<td>101</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td>000</td>
<td></td>
</tr>
<tr>
<td>-1</td>
<td>100</td>
<td>110</td>
<td>010</td>
<td>011</td>
<td>001</td>
<td>101</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>011</td>
<td>001</td>
<td>101</td>
<td>110</td>
<td>010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1</td>
<td>001</td>
<td>101</td>
<td>100</td>
<td>110</td>
<td>010</td>
<td>011</td>
<td></td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>S1</th>
<th>S12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase V1, V2 and V6</td>
<td>V1, V2 and V6</td>
</tr>
<tr>
<td>Decrease V3, V4 and V5</td>
<td>V3, V4 and V5</td>
</tr>
</tbody>
</table>

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 4 rad/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.
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.

Figure 8 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.

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.

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],
      (Input: 100A peak max, DC. 100kHz/output:100-10mV/A, 1V peak max.
   b: Current: AM30N 10-100A/1V,
   c: Voltage: Differential DP1000 with two outputs 10-100mV/A, 1V peak max.

Fig.12. Testbed used in the present study.

Table 6. IM parameters used in this study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole pairs p</td>
<td>2</td>
</tr>
<tr>
<td>Rated power kW (at 50 Hz)</td>
<td>4</td>
</tr>
<tr>
<td>Rated voltage (V)</td>
<td>220/380</td>
</tr>
<tr>
<td>Stator resistance R_s (Ω)</td>
<td>1.30</td>
</tr>
<tr>
<td>Rotor resistance R_r (Ω)</td>
<td>0.91</td>
</tr>
<tr>
<td>Self-inductance (stator &amp; rotor) L_{sr} (H)</td>
<td>0.19</td>
</tr>
<tr>
<td>Mutual inductance M (H)</td>
<td>0.18</td>
</tr>
<tr>
<td>J(㎏.m²)</td>
<td>0.009</td>
</tr>
<tr>
<td>f_r (N.m.s/rad)</td>
<td>0.03</td>
</tr>
</tbody>
</table>

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References