This study focuses on the design and construction of a power to direct torque control of double star induction machine. After modeling the induction machine, the voltage source inverter and the DTC technique are defined and described. For a double star induction machine the voltage source inverter adapted is a six phase topology. This latter is composed of 12 IGBT connected in antiparallel with 12 fast diodes. The control technique is implemented on the DSP board based on TMS320LF2407A which allows a great flexibility in the control, quite large execution speed and real time program flow. The system was tested experimentally. The obtained results show the effectiveness of the technique and the system.

Keywords: Double star induction motor, direct torque control, DSP TMS320LF2407A, switching table.

1. Introduction

Since the appearance of induction and synchronous AC machines, the three-phase structure has quickly established itself in the industrial world. The induction machine is currently the most used in industrial drive systems because of its numerous advantages: simplicity of its control, robustness and low cost [1] [2].

In the industrial applications where high reliability is required, multi-phase induction machines instead of traditional three-phase machines are used. In the multi-phase drive systems, the electric machine has more than three phases in the stator and the same number of inverter legs is in the inverter side. The advantages of multi-phase drive systems are: total rating of system is multiplied, the torque pulsations will be smoothed, the rotor harmonic losses as well as the harmonics content of the DC link current will be reduced and the loss of one or more phases does not prevent the machine working, so improving the system reliability. The most common multiphase machine drive structure is the double star induction motor (DSIM), which has six windings in the stator.[3],[4].

The development of power semiconductors has created fast switches used in power converters. They offer great flexibility of use and simplify drive systems of induction machines. The digitization of the control of these converters, with the emergence of processors, has made these structures faster and more reliable, which helped to spread this technology in the industry where they undergo great stress [5], [6], [7]. So multiphase machines are increasingly sought as they have the advantages of the distribution of power and reliable operation, their advantages appear at a high power systems especially [8], [9].

Direct torque control (DTC) of induction motors, which has been developed in the recent decade, is powerful control method for motor drives [10],[11], [12]. Featuring direct control of the stator flux and torque instead of the conventional current control technique, it provides a systematic solution to improve operating characteristics of not only the motor but also the voltage source inverter (VSI).
In principle, DTC method is based on instantaneous space vector theory. By optimal selection of space voltage vectors in each sampling period, DTC achieves effective control of the stator flux and torque. [13]. In this paper, the DTC is developed double star induction motor Implementation on TMS320LF2407A digital signal processor (DSP) is discussed, and experimental results carried out for this machine are given.

2. DESCRIPTION OF THE SYSTEM

The total system is composed of two parts: The part of power and the part of control. The premiere represents the power part of the test bench it comprises the source of continuous tension, the inverter six arms and the machine doubles star. On the other hand, in the second part one finds the part orders which are consisted of the chart of to DSP TMS320LF2407A with its development platform, the chart of insulation and the converters analogical/numeric and numeric/analogue.

The double star induction machine is a machine that has two identical three-phase stator windings shifted with respect to each other to an electrical angle \( \alpha \). (in our case the angle equal to \( \pi/6 \)). Phases (1.2.3) of the first stator are offset relative to each other at an angle of \( 2\pi/3 \). Phases (4.5.6) of the second stator are offset relative to each other at an angle of \( 2\pi/3 \). The return current in the stator (1) and stator (2) is isolated by the neutral. The rotor of the double star induction machine is identical to that of a conventional three phase induction machine [5].

3. MODELING

To derive the machine model of a double star induction motor (DSIM), the following assumptions have been made: space harmonics, magnetic saturation, and core losses are neglected. In the same way as for three-phase systems, the use of a \( 6 \times 6 \) transformation matrix allows the stator variables to be expressed in an orthogonal base [13], [14].

Figure 2 shows a diagram of the stator which is composed of two stator winding shifted by an angle \( \alpha \) and a three phase rotor winding shorted.
3.1 Machine model in (d-q) subspace

\[
\begin{align*}
\dot{v}_{sd1} &= r_{s1}i_{sd1} + \frac{d\phi_{sd1}}{dt} - \Omega_s\phi_{sq1} \\
\dot{v}_{sq1} &= r_{s1}i_{sq1} + \frac{d\phi_{sq1}}{dt} + \Omega_s\phi_{sd1} \\
\dot{v}_{sd2} &= r_{s2}i_{sd2} + \frac{d\phi_{sd2}}{dt} - \Omega_s\phi_{sq2} \\
\dot{v}_{sq2} &= r_{s2}i_{sq2} + \frac{d\phi_{sq2}}{dt} + \Omega_s\phi_{sd2} \\
0 &= r_s i_{rd} + \frac{d\phi_{rd}}{dt} - (\Omega_s - \Omega_r)\phi_{rq} \\
0 &= r_s i_{rq} + \frac{d\phi_{rq}}{dt} + (\Omega_s - \Omega_r)\phi_{rd}
\end{align*}
\]

Where:

\[
\begin{align*}
\phi_{sd1} &= L_{s1}i_{sd1} + L_m(i_{sd1} + i_{sd2} + i_{rd}) \\
\phi_{sq1} &= L_{s1}i_{sq1} + L_m(i_{sq1} + i_{sq2} + i_{rq}) \\
\phi_{sd2} &= L_{s2}i_{sd2} + L_m(i_{sd1} + i_{sd2} + i_{rd}) \\
\phi_{sq2} &= L_{s2}i_{sq2} + L_m(i_{sq1} + i_{sq2} + i_{rq}) \\
\phi_{rd} &= L_r i_{rd} + L_m(i_{rd1} + i_{rd2} + i_{rd}) \\
\phi_{rq} &= L_r i_{rq} + L_m(i_{sq1} + i_{sq2} + i_{rq})
\end{align*}
\]
\[ L_m = \frac{3}{2} L_{sr} = \frac{3}{2} L_{rs} \]

Where: \( L_{s1} = L_{q2} \) is the stator leakage inductance of (d-q) equivalent circuit, and \( L_m \) is mutual leakage inductance.

\[ \int d \Omega = C_{em} - C_r - K_r \Omega \]  \hspace{1cm} (3)

### 3.2 Electromagnetic torque expression

The electromagnetic torque expression of the double star induction motor becomes:

\[ C_{em} = p \left[ \frac{1}{2} i_{sq1} + \frac{1}{2} i_{sq2} \right] \Omega \]  \hspace{1cm} (4)

Where: \( p \) is the number of poles pairs.

### 4. DTC METHOD FOR DOUBLE STAR INDUCTION MOTOR

As described previously, the goal of DTC of double star induction motor is to maintain the stator flux and torque within the limits of flux and torque hysteresis bands by proper selection of the stator space voltage vectors during each sampling period. The voltage vectors are selected according to the errors of stator flux and torque. Table 1 summaries the combined effects of each voltage vector on both the stator flux and torque [10], [11], [15].

For effective control of the torque of polyphase machine it is imperative to properly adjust the flux. To do this we place ourselves in a fixed frame \((\alpha, \beta)\) related to the stator of the machine. The following equation allows us to set the behavior of stator flux.

\[ V_s = R_s I_s + \frac{d}{dt} \frac{\Phi_s}{L_s} = \frac{\Phi_s}{L_s} + \int (V_s - R_s I_s) dt \]  \hspace{1cm} (5)

The expression of the electromagnetic torque is given by the following equation:

\[ C_{em} = k (\Phi_s \times \Phi_r) = k. \| \Phi_s \|. \| \Phi_r \|. \sin \lambda \]  \hspace{1cm} (6)

From the expressions of the flux and torque, as well as expressions of the two stator voltage vector of the double star induction machine, in the fixed system \((\alpha, \beta)\) are given by the following equation.

\[ [V_{\alpha1}] = [P(0)].[V_{a1b1c1}] \]

\[ [V_{\beta1}] = \frac{j}{\sqrt{3}} \begin{bmatrix} \sqrt{2} & -\frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \sqrt{2} & -\frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2} & \sqrt{2} \end{bmatrix} [V_{\alpha1}] \]

\[ \frac{d}{dt} \]  \hspace{1cm} (7)

\[ [V_{\alpha2}] = \frac{1}{\sqrt{3}} \begin{bmatrix} \sqrt{2} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \sqrt{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & \sqrt{2} \end{bmatrix} [V_{\alpha2}] \]

\[ [V_{\beta2}] = \frac{1}{\sqrt{3}} \begin{bmatrix} \sqrt{2} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \sqrt{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & \sqrt{2} \end{bmatrix} [V_{\beta2}] \]  \hspace{1cm} (8)

\[ \text{in our case } \delta = 30^\circ \]
The new expressions of stator voltages allow us to calculate in real time and at any moment magnitudes flux and torque, using the following equations:

\[ \emptyset_{sak} = \int_0^t (V_{sak} - R s_i s_{ak}) dt \]
\[ \emptyset_{s\beta k} = \int_0^t (V_{s\beta k} - R s_i s_{\beta k}) dt \]

With \( k=1, 2 \)

Thus, the stator flux module is written:

\[ \emptyset_s = \sqrt{(\emptyset_{s\alpha 1} + \emptyset_{s\alpha 2})^2 + ((\emptyset_{s\beta 1} - \emptyset_{s\beta 2})^2)} \]  

(9)

The angle \( \theta_s \), shift vector \( \emptyset_s \) is given by the following expression:

\[ \theta_s = \arctg \left( \frac{\emptyset_{s\alpha 1} + \emptyset_{s\alpha 2}}{\emptyset_{s\beta 1} + \emptyset_{s\beta 2}} \right) \]  

(10)

The calculation of the stator flux is not sufficient to control the torque of the machine. An estimate of the torque in real time is required. For this, an expression of the torque was included in the program,

\[ C_{em} = p. [\emptyset_{a1}i_{\beta 1} + \emptyset_{a2}i_{\beta 2} - \emptyset_{\beta 1}i_{a1} + \emptyset_{\beta 2}i_{a2}] \]  

(11)

4.1 Controllers Elaboration

The Modeling of the machine allowed us to obtain equations of flux and torque in a single fixed reference. From the previous section, the flux and the torque expressions are found in a single fixed reference frame.

4.2 Stator Flux estimation

To maintain a constant amplitude flux \( (\emptyset_s) \) for the stator flux \( (\emptyset_s) \) which means to have a circular trajectory in the referential \((u, \beta)\), with a limited set of vectors delivered by the switching power converter, we introduce a correction flux. When the flux is in the zone I, the vectors \( V_l, V_{l+1}, V_{l-1} \) are chosen to increase the amplitude of flux. Its decrease is ensured by the selection of vectors, \( V_{l+2}, V_{l-2} \), the zero voltage vector does not nearly affect the magnitude of the stator flux. The choice of the hysteresis correction at two levels seems to be the simplest and most suitable for control study. This shows that the choice of voltage vector depends on the sign of the error of the flux and independent of the amplitude of the error [10].

This explains that the output of the corrector flux may be a Boolean variable.

C\( \text{flx}=1 \): when the error flux is positive.
C\( \text{flx}=0 \): when the error flux is negative.
4.3 Electromagnetic torque control

To control the electromagnetic torque, two types of hysteresis comparators can be used: Correction at two levels and Correction at three levels.

4.3.1 The correction at three levels

The three levels comparator allows us to control the machine in both directions of rotation, either for positive torque or negative torque. Thus, the comparator at three levels gives the possibility to operate in four quadrants without changing the command structure.

4.3.2 The corrector at two levels

The use of two level comparator allows to control the torque in one direction of rotation. The change of direction of rotation can be achieved by swapping two phases of the machine. To move the stator flux vector, only one vectors $V_{t+1}$ and $V_{t+2}$ can be selected. Therefore, the decrease in torque is achieved only by selecting the zero vectors.

The application of a vector $V_{t-1}$ after $V_{t+1}$, or vice versa, switching leads in two different arms of the inverter. And so it is well to apply $V_{t-2}$ after $V_{t+2}$ and vice versa. There is always a zero voltage vector that can be applied after a non-zero voltage vectors, the torque may increase or decrease.

The use of the zero vectors has the advantage, in addition to slower changes of the torque, a decrease in the number of commutations. Moreover, the nature of the zero vectors applied can be chosen so as to reduce further the number of commutations.

- $V_{t+1} \Leftrightarrow V_{t-1}$: Commutation in two arms of the inverter.
- $V_{t+2} \Leftrightarrow V_{t-2}$: Commutation in two arms of the inverter.
- $V_1, V_3, V_5 \Leftrightarrow V_0$: Commutation in one arm of the inverter.
- $V_2, V_4, V_6 \Leftrightarrow V_7$: Commutation in one arm of the inverter.
One knows that the principal of direct torque control is based on the choice of the applied vector voltage gotten from the output of hysteresis controller. The following table summarizes the different possible combinations [11].

<table>
<thead>
<tr>
<th>$\theta_s$</th>
<th>$V_{i-2}$</th>
<th>$V_{i-1}$</th>
<th>$V_i$</th>
<th>$V_{i+1}$</th>
<th>$V_{i+2}$</th>
<th>$V_{i+3}$</th>
<th>$V_0, V_7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{em} (&gt;0)$</td>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
<td>$\uparrow$</td>
<td>$\downarrow$</td>
<td>$\uparrow$</td>
<td>$\downarrow$</td>
<td></td>
</tr>
<tr>
<td>$C_{em} (&lt;0)$</td>
<td>$\downarrow$</td>
<td>$\uparrow$</td>
<td>$\uparrow$</td>
<td>$\uparrow$</td>
<td>$\downarrow$</td>
<td>$\uparrow$</td>
<td></td>
</tr>
</tbody>
</table>

**Tab1:** Variations of the torque and flux as a function of the vector on.

Several voltage vectors can be selected for a given combination of flux and torque. The choice is made on the basis of a predefined strategy and each of them (combinations) affects the torque ripple of the current, dynamic performances and operation of two or four quadrants.

In our case, we opted for a four quadrant operation with a two level comparator for the torque. The following table shows the different choices of the voltage vector to be applied according to the results given to the output of both flux and torque comparators [11].

<table>
<thead>
<tr>
<th>N</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ccpl</td>
<td>1</td>
<td>Cflx</td>
<td>$V_2$</td>
<td>$V_3$</td>
<td>$V_4$</td>
<td>$V_5$</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>$V_3$</td>
<td>$V_4$</td>
<td>$V_5$</td>
<td>$V_6$</td>
<td>$V_1$</td>
</tr>
<tr>
<td>Ccpl</td>
<td>0</td>
<td>Cflx</td>
<td>$V_6$</td>
<td>$V_1$</td>
<td>$V_2$</td>
<td>$V_3$</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>$V_5$</td>
<td>$V_6$</td>
<td>$V_1$</td>
<td>$V_2$</td>
<td>$V_3$</td>
</tr>
</tbody>
</table>

**Tab2:** four quadrant operation.

### 5. NUMERICAL SIMULATION

In the aim to show the effectiveness of the DTC applied to double star induction motor a numerical simulation is done in the MATLAB/Simulink software. The results are shown in figures 4-7.

**Fig4.** Shape of the current phase of the machine.
For the selected table, the obtained results are satisfactory. This is because of the flux oscillations round the reference imposed value. This forms a circle shell of radius equal to its reference. Figure (fig7) shows the electromagnetic torque where it represents a small ripple around the reference imposed value. At startup, we find strong undulations as a result of the variations of the flux and currents during this time interval but soon the pair approaches the reference value and the ripples are greatly reduced.

6. REALIZATION
As we have already described our model has two essential parts. The control board contains TMS320LF2407A controlled by a computer via development software LF2407
studio code. The insulating part which is essentially made to amplify the control signals generated by the DSP to ensure saturation of the IGBT, galvanic isolation so the control circuit of the power circuit and interlock when electrical problem arises. And the driver that comes after the opto-coupler. This is the IR 2130 integrated circuit intended for driving six IGBTs. It provides them with the saturation and creates a floating mass for each arm. This circuit is also provided for system protection against over current or sudden change of current imposed on IGBTs. In addition he created himself down time for each arm and will prevent the short circuit of the DC voltage source.

Fig8. The test bench realized.

The second part consists of a voltage inverter with six arms, powered by a DC voltage source Us. For each IGBT, a switching diode is connected in inverse. All feeds a cage induction machine of 4.5 Kw.

7. Experimental Tests

To test the performance of the test bed made, we made some tests on the Double Star induction motor (DSIM) a power of 4.5kW by applying the technique of Direct Torque Control. The results obtained are illustrated below:

Fig9. The phase current
The Fig.9 illustrates the experimental results, as it can be seen on this figure the waveform of current is practically sinusoidal, and on the Fig.10 and Fig.11, we can see low frequency ripples appear on the flux and torque these results confirm the efficiency of the control scheme.

9. CONCLUSION

In this paper, we presented the implementation of the direct torque control (DTC) of double star induction motor based on DSP board TMS320LF2407A. In order to confirm the feasibility of the control scheme and to validate the simulation results, a set of experimental results are presented. It must be noticed that the results are identical and satisfactory between experimental and simulation. We see the decoupling of flux and torque which tends to its reference value imposed even if it presents little variation can be explained by that the machine has made large mutual and errors committed when calculating the flux and torque. Thanks to this method we can impose specific guidelines as to the machine direction of rotation, the reference torque and speed.
The machine parameters used are:

- \( R_s = 3.72 \Omega \): stator resistance
- \( L_s = 0.022 \text{H} \): own stator cyclic induction
- \( R_r = 2.12 \Omega \): rotor resistance
- \( L_r = 0.006 \text{H} \): own cyclic inductance of the rotor
- \( M = 0.3672 \text{H} \): cyclic mutual inductance main
- \( J = 0.662 \text{Kg.m}^2 \): moment of inertia of the rotating part
- \( F = 0.001 \text{N.m.s/rad} \): viscous friction coefficient
- \( U = 220 \text{V} \): single voltage supply.

**References**


**APPENDIX**

The machine parameters used are: