Direct Torque Control of Induction Motor Based on Space Vector Modulation Using a Fuzzy Logic Speed Controller

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**ABSTRACT** - In the paper, the proposed direct torque control using space vector modulation is based on fuzzy logic technique to replace proportional integral regulator PI anti-windup of the speed of induction motor, in order to reduce torque, flux ripples and get swifter response velocity in comparison with the conventional DTC based on SVM. The MATLAB SIMULINK programming environment is used as a simulation tool. The results obtained, shows the importance of this control method.

**KEYWORDS**: Induction motor IM, direct torque control DTC, space vector modulation SVM, proportional integral PI, Fuzzy Logic controller FL

1. INTRODUCTION

High dynamic performance of induction motor drives is indispensable in many applications of today’s automatically controlled machines. Induction motor control has attracted much attention recently in the power electronics field. Vector control based in rotor flux orientation presents a major disadvantage to be relatively sensible to the machine parameters variation, for such reason the direct torque control (DTC) methods of the induction machines have been developed during the nineties[1]. The basic concept is to control both stator flux and electromagnetic torque of the machine simultaneously. Its simple structure is due to the use two hysteresis comparators and switching vector tables for both flux and torque control. The hysteresis controller is usually a two-value bang-bang controller, which results in taking the same action for the big torque error and small torque error. Thus it may produce big torque ripple [2].

To overcome the above problems, so far a few researchers have presented, the DTC scheme using the space vector modulation (SVM) techniques.

To control the speed of an induction motor driven by the DTC-SVM. The Proportional-Integral controller is always the preferred choice. This is because the implementation of the PI controller requires minimal information about the motor, where the controller gains are tuning until a satisfactory response is obtained [3].

As, the induction motor is naturally a non-linear system and is subjected to parameter variations, external disturbances, and non-linear loads, PI controller may not give satisfactory performance when subjected to these conditions as shown by [4].

Now a day’s fuzzy logic is considered an interesting alternative approach for its advantages: analysis close to that of the man operator, ability of nonlinear systems control, best dynamic performances and the inherent quality of robustness.

The objective of this paper, first to solve the problems of torque ripple and inconstant switch frequency of inverter in the conventional direct torque control, a new DTC-SVM method for a speed control of AC motor drive is proposed, second, to control the speed of AC motor driven by DTC-SVM using fuzzy controller In order to improve swift response, small overshooting and fine precision in high and low speed.

2. PRINCIPLE

Using the vectorial expressions the machine in the reference frame binds to the stator is defined by:

\[
\begin{align*}
V_s &= R_s i_s = \frac{d\Phi_s}{dt} \\
V_r &= 0 = R_r i_r + \frac{d\Phi_r}{dt} - j\omega \Phi_r.
\end{align*}
\]

From the flux expressions, the rotor current can be written

\[
\bar{I}_r = \frac{1}{\sigma} \left( \frac{\Phi_r}{L_s} - \frac{\sigma}{L_s L_m} \Phi_s \right)
\]

With \( \sigma = 1 - \frac{L_m^2}{L_s L_r} \) (variability (scatter) factor)

The equations become:
\[
\begin{aligned}
\frac{d\Phi_r}{dt} + \left(\frac{1}{\sigma_r} - j\omega\right)\Phi_r &= \frac{L_m}{L_r} \frac{1}{\sigma_r} \Phi_s \\
\end{aligned}
\]

These relations show that:

- We can possibly control the \(\Phi_s\) vector starting from \(\Phi_r\) vector, with the voltage drop \(R_r \Delta I\).
- The flux \(\Phi_r\) follows the variation of \(\Phi_s\) with time constant \(\sigma_r\).
- The electromagnetic torque is proportional to the vectorial product of the stator and rotor flux vectors.

\[
\Gamma_{elm} = \frac{L_m}{\sigma L_r} \Phi_s \Phi_r \sin \gamma
\]

With \(\gamma = (\Phi_s, \Phi_r)\).

Thus the torque depends on the amplitude and the relative position of the two vectors \(\Phi_s\) and \(\Phi_r\).

If we manage to control perfectly the flux \(\Phi_s\) (starting from \(V_s\)) in module and position, we can thus control the amplitude and the relative position of \(\Phi_s\) and \(\Phi_r\), consequently the torque. This can be possible only when the control period \(T_s\) of the voltage \(V_s\) is such as \(T_s \ll \sigma_T\). [5]

3. DTC SPACE VECTOR MODULATION

The structure of the DTC space vector modulation with fuzzy controller speed as follows:

4. ADVANTAGES OF DTC-SVM

In the DTC system, the same active voltage vectors are applied during the whole sample period, and possibly several consecutive samples which give rise to relatively high ripple in stator current, flux linkage and torque. One of proposals to minimise these problems is to introduce Space Vector Modulation (SVM), which is a pulse width modulation technique that able to synthesise any voltage vector lying inside the sextant spanned by the six PWM voltage vectors.

In this method DTC–SVM has proved to generate very low torque and flux ripple while showing almost as good dynamic performance as the DTC system. The DTC-SVM systems, though being a good performer, but introduce an extra complexity [6].

The fluctuation of the IM torque has a closed relationship to the deviation from an ideal rotation stator flux vector \(\Phi_{s ref}\) which has a constant rotational speed and a constant length. The difference between \(\Phi_{s ref}\) and \(\Phi_s\), which is generated in three-phase PWM inverter, cause torque pulsation. The relationship between torque pulsation \(\Delta \Gamma_e\) and the deviation of \(\Phi_s\) from \(\Phi_{s ref}\) has been deduced as:

\[
\frac{\Delta \Gamma_e}{\Gamma_{s ref}} = k_s \left|\Delta \Phi_s\right| + k_s \Delta \delta
\]

Where \(\Gamma_{s ref}\) is the steady state torque \(\Delta \Phi_s\) and \(\Delta \delta\) are respectively the deviations from |\(\Delta \Phi_s\)| and \(\delta\) which are defined by:

\[
\Delta \Phi_s = |\Phi_{s ref}| - |\Phi_s|
\]

\[
\Delta \delta = \angle \Phi_{s ref} - \angle \Phi_s
\]

Where \(k_s\) and \(k_\delta\) are the constants derived from the IM specifications.

The torque ripple is actually caused by \(\Delta \Phi_s\) and \(\Delta \delta\) and the influence of the \(\Delta \Phi_s\) is considerably smaller than that of \(\Delta \delta\). As a consequence the torque ripple can be almost removed if \(\Delta \delta\) is kept close to zero.

In Fig.1 one can notice that the torque error \(\Delta \Gamma_e\) and reference stator flux amplitude \(|\Phi_{s ref}|\) are delivered to voltage vector calculation which in its input gives the deviation of reference stator flux angle.

From the \(\alpha, \beta\) axes components of the stator reference voltage \(V_{s ref}\), are calculated as:

\[
V_{s\alpha ref} = \frac{\Phi_{s ref} \cos(\delta + \Delta \delta) \cdot \Phi_{s ref} \cos(\delta)}{T_s} + R_s I_{s\alpha}
\]

\[
V_{s\beta ref} = \frac{\Phi_{s ref} \sin(\delta + \Delta \delta) \cdot \Phi_{s ref} \sin(\delta)}{T_s} + R_s I_{s\beta}
\]

Where the vector magnitude and angle are given as,
\[ V_{s\text{ ref}} = \sqrt{V_{s}^2 + V_{\beta}^2} \]  
\[ \delta = \arctan \left( \frac{V_{\beta\text{ ref}}}{V_{s\text{ ref}}} \right) \]  

Where, \( T_s \) is the sample time of system

5. VOLTAGE SPACE VECTOR MODULATION

The voltage vectors, produced by a 3-phase inverter, divide the space vector plane into six sectors as shown in Fig.3.

\[ V_{s\text{ ref}} = \sqrt{V_{s\text{ ref}}^2 + V_{\beta\text{ ref}}^2} \]  
\[ \delta = \arctan \left( \frac{V_{\beta\text{ ref}}}{V_{s\text{ ref}}} \right) \]  

Where, \( T_s \) is the sample time of system

![Fig. 2. Representation of stator flux vectors \( \Phi_d \) and \( \Phi_q \).](image)

![Fig. 3. Diagram of the inverter exported voltage space vector.](image)

In every sector, the arbitrary voltage vector is synthesised by basic space voltage vector of the two side of sector and one zero vector. For example, in the first sector, \( V_s \) is a synthesised by the voltage space vector equations (10) and (11),

\[ V_{s\text{ ref}} = V_{s\text{ ref}} T_0 + V_{\beta\text{ ref}} T_1 + V_2 T_2 \]  
\[ T_s = T_0 + T_1 + T_2 \]  

Where, \( T_s \) is the sample time of system, \( T_0 \), \( T_1 \) and \( T_2 \) are the work times of basic space voltage vector \( V_0 \), \( V_1 \) and \( V_2 \) respectively Fig. 4; with \( T_1 \) and \( T_2 \) are given by simple projections:

\[ T_1 = \frac{T_s}{2} \left( \sqrt{6} V_{s\beta\text{ ref}} - \sqrt{2} V_{s\text{ ref}} \right) \]  
\[ T_2 = \frac{\sqrt{2} T_s}{E} V_{s\beta\text{ ref}} \]  

The rest of the period spent in applying the null-vector. For every sector, commutation period is calculated. The amount of times of vector application can all be related to the following variables: [7].

\[ X = \frac{T_s}{E} \sqrt{3} V_{s\beta\text{ ref}} \]  
\[ Y = \frac{T_s}{E} \left( \sqrt{2} V_{s\beta\text{ ref}} + \sqrt{6} V_{s\text{ ref}} \right) \]  
\[ Z = \frac{T_s}{E} \left( \sqrt{2} V_{s\beta\text{ ref}} - \sqrt{6} V_{s\text{ ref}} \right) \]  

Table 1. Applications durations of the sectors boundary

<table>
<thead>
<tr>
<th>Sector</th>
<th>T1</th>
<th>T2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Z</td>
<td>Y</td>
</tr>
<tr>
<td>2</td>
<td>Y</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>Z</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>5</td>
<td>X</td>
<td>-Y</td>
</tr>
<tr>
<td>6</td>
<td>-Y</td>
<td>-Z</td>
</tr>
</tbody>
</table>

The third step is to compute the three necessary duty cycles as:

\[ T_{aon} = \frac{T_s - T_1 - T_2}{2} \]  
\[ T_{bon} = T_{aon} + T_1 \]  
\[ T_{con} = T_{bon} + T_2 \]  

The last step is to assign the right duty cycle (\( T_{xon} \)) to the right motor phase according to the sector.

Table 2. Assigned duty cycle to the PWM outputs

<table>
<thead>
<tr>
<th>Sector</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sa</td>
<td>Tb</td>
<td>Taon</td>
<td>Taon</td>
<td>Tcon</td>
<td>Tbon</td>
<td>Tbon</td>
</tr>
<tr>
<td>Sb</td>
<td>Taon</td>
<td>Tcon</td>
<td>Tbon</td>
<td>Tbon</td>
<td>Tcon</td>
<td>Taon</td>
</tr>
<tr>
<td>Sc</td>
<td>Tcon</td>
<td>Tbon</td>
<td>Tcon</td>
<td>Taon</td>
<td>Taon</td>
<td>Tbon</td>
</tr>
</tbody>
</table>
6. MACHINE CONTROL WITH FUZZY CONTROLLER

In the objective to cancel the static error and to reduce the time response while preserving the system stability, the proportional integral corrector PI used is replaced with a fuzzy logic regulator.

6.1. Fuzzy logic regulator.

The block diagram of the loop is made up mainly of the process to control, fuzzification blocks, inference and defuzzification where we define the membership functions of \( \varepsilon \), \( \Delta \varepsilon \), and \( \Delta u \) for the first, fuzzy rules and their deduction for the second and the conversion of fuzzy variable into deterministic value for the third, of standardization factors (G0, G1 and G2) respectively associated at the input \( \varepsilon = \omega_{\text{ref}} - \omega \), also its variation \( \Delta \varepsilon \) and the control variation \( \Delta u \) [8].

![Fig. 5. Fuzzy logic controller topology.](image)

6.2. Fuzzification

It rests on a positioning of the fields of possibilities in fuzzy subsets.

For our case the regulator has two inputs \( \varepsilon \), \( \Delta \varepsilon \) and for the fuzzyfied outputs \( \Delta u \) as follow: for \( \varepsilon \) et \( \Delta u \), we have seven linguistic terms (NS, NM, NB, EZ, PS, PM, PB) and for \( \Delta \varepsilon \) only three which are (N, EZ, P), each one of them is defined by a membership function of the triangular type according to figures 6 and 7.

\[
\begin{array}{cccccc}
\text{NS} & \text{NM} & \text{NB} & \text{EZ} & \text{PS} & \text{PM} & \text{PB} \\
-1 & -0.75 & -0.5 & -0.25 & 0 & 0.25 & 0.5 & 0.75 & 1
\end{array}
\]

![Fig. 6. Fuzzy subset \( \varepsilon \) and \( \Delta u \).](image)

\[
\begin{array}{cccc}
\text{N} & \text{EZ} & \text{P} \\
-1 & -0.7 & -0 & -0.25 & 0 & 0.25 & 0.5 & 0.75 & 1
\end{array}
\]

![Fig. 7. Fuzzy subset \( \Delta \varepsilon \).](image)

6.3. Rules

The set of rules is described according to Mac Vicar with the format If-Thus under the fuzzy rules table with two inputs variables according to:

![Table 3. Decision table Mac Vicar](image)

### 6.4. Interfacing

The choice of the inference method depends upon the static and dynamic behavior of the system to regulate, the control unit and especially on the advantages of adjustment taken into account.

We have adopted the inference method Max-Min because it has the advantage of being easy to implement on one hand and gives better results on the other hand [9].

### 6.5. Defuzzyfication

The most used defuzzification method is that of the center of attraction of balanced heights, our choice is based on the latter owing to the fact that it is easy to implement and does not require much calculation [10].

7. SIMULATIONS RESULTS

In order to illustrate the improvements that offers a fuzzy regulator with regards to a classic PI for the static and dynamic performances of the control of the asynchronous machine with DTC using space vector modulation., we led a study of simulation with the same test conditions such as the three transitory modes: a load less starting, an introduction of a load torque and the inversion of the direction of speed rotation, and to test the control robustness with respect to the parametric variations.

**7.1.1. Introduction of load torque**

To test the adjustment robustness of the induction machine with fuzzy logic controller we have introduced a load torque of 25N.m at \( t=0.5s \) and to examine more this test we have used a step of instruction of 25N.m at \( t=0.5s \), see figure 8. It is noted that the speed reaches its reference \( \omega_{\text{ref}} = 100\text{rad/s} \) without going beyond and that the disturbance rejections due to the applied instructions of loads at the various above mentioned moments are eliminated in contrast to that observed during the adjustment by classic PI see figure 7. It is also noted that the regulation effect persists always, indeed the electromagnetic torque acts very quickly to follow the instructions of introduced loads and presents a remarkable reduction in the harmonics.

**7.1.2. Inversion of speed direction of rotation**

Figure 8 illustrates clearly the robustness of fuzzy regulator particularly the speed response with regards to a significant inversion of its reference from 100rad/s to -100rad/s, and for low speed for 20rad/s to -20 rad/s it is clearly noted that the speed is established without
going beyond and converges quickly to its reference. However the electromagnetic torque marks a peak at starting and another reverse at the change of the speed direction of rotation but the braking time at starting in the reverse direction is relatively shorter than that obtained by a classic PI.

8. CONCLUSION

In this article we have introduced the principles of the fuzzy logic control and justifying our choice of this method for the control of asynchronous machines. After having chosen the method of Simulink simulation and having confirmed its effectiveness, we have used this simulation under several operating conditions in order to exploit with exactness the different results obtained. Thus it was clearly shown that fuzzy controller exceeds classic regulator. But in spite of the robustness of FLC fuzzy logic controller for all the considered variations (load torque and inversion of the speed direction of rotation) with respect to classic PI, nevertheless there are certain reserves on the characteristics of this new control technique when the operating conditions change in large band. In conclusion, it is believed that the DTC using SVM principle will continue to play a strategic role in the development of high performance drives.

REFERENCES

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