Direct Torque Control of Induction Motors

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1. Introduction

D.C. motors have been used widely during the last century in applications where variable-speed operation was needed, because its flux and torque can be controlled easily by means of changing the field and the armature currents respectively. Furthermore, operation in the four quadrants of the torque-speed plane including temporary standstill was achieved. However, DC motors have basically two drawbacks, which are the existence of commutators and brushes. These two disadvantages implied not only periodic maintenance but also difficulty to work in dirty and explosive environments; difficulty that sometimes used to become in impossibility.

On the other hand, induction motors are robust, easily maintained and reliable. Moreover the cost is lower, as well as the inertia and the weight.

Nowadays, the inverters can act a very fast switching frequency and the cost of the computers is decreasing. Due to the advantages and the positive circumstances explained above, induction motors are replacing DC motors in the industry applications, even in the applications where a fast speed and torque response in four quadrants is required, becoming the new horsepower of the industry.

At present, 67% of all the electrical energy generated in the UK is converted to mechanical energy for utilisation.

In Europe the electrical drives business is worth approximately $1.0 Billion/ Annum.

1. Types of Controllers

There are many different ways to drive an induction motor. The main differences between them are the motor’s performance and the viability and cost in its real implementation.

1.1- Voltage/Frequency:

Despite the fact that V/F is the simplest controller, it is the most widespread, reaching approximately 90% of the industrial applications. It is known as a scalar control and acts imposing a constant relation between voltage and frequency. The structure is very simple and it is normally used without speed feedback. However, this controller doesn’t achieve a good accuracy in both speed and torque responses mainly due to the fact that the stator flux and the torque are not directly controlled. Even though, as long as the parameters are identified, the accuracy in the speed can be 2% (except in a very low speed) and the dynamic response can be approximately around 50ms [2][3].

1.2- Vector Controllers:

In these types of controllers, there are control loops for controlling both the torque and the flux [3]. The most spread controllers are the ones that use vector transform such as either Park or Ku. Its accuracy can reach values such as 0.5% regarding the speed and 2% regarding the torque, even in stand still. The main disadvantages are the huge computational capability required and the compulsory good identification of the motor parameters.

1.3- Field Acceleration Method:

This method is based on maintaining the amplitude and the phase of the stator current constants, avoiding electromagnetic transients. Therefore the equations used can be simplified saving the vector transformation in the controllers.

It is achieved some computational reduction, overcoming the main problem in the vector controllers and then becoming an important alternative for the vector controllers.

2. Direct Torque Control

2.1- Introduction:

In DTC it is possible to control directly the stator flux and the torque by selecting the appropriate inverter state.

Its main features are as follows:

1/ Direct control of flux and torque.
2/ Indirect control of stator currents and voltages.
3/ Approximately sinusoidal stator fluxes and stator currents. 
4/ High dynamic performance even at stand still locked rotor.

This method presents the following advantages:
1/ Absence of co-ordinate transform. 
2/ Absence of voltage modulator block, as well as other controllers such as PID for motor flux and torque. 
3/ Minimal torque response time, even better than the vector controllers. 

Although, some disadvantages are present:
1/ Possible problems during starting. 
2/ Requirement of torque and flux estimators, implying the consequent parameters identification. 
3/ Inherent torque and flux ripple. 

2.2- DTC Principles: 
It is well known that in the three-phase induction machines the electromagnetic torque can be expressed as follows [2][3]:

\[ t_p = \frac{3}{2} \frac{m}{s} \times \tilde{i}_s \]  

Where \( \tilde{\psi}_s \) is the stator flux, \( \tilde{i}_s \) is the stator current (both fixed to the stationary reference frame) and \( P \) the number of pairs of poles. The previous equation can be modified and expressed as follows:

\[ t_e = -\frac{3}{2} P \tilde{\psi}_s \times \tilde{i}_s \]  

Where \( \rho_s \) is the stator flux angle and \( \alpha_s \) is the stator current one, both referred to the horizontal axis of the stationary frame fixed to the stator. 

If the stator flux is kept constant and the angle \( \rho_s \) is changed quickly, then the electromagnetic torque can be changed in a fast way.

The same conclusion can be obtained using another expression for the electromagnetic torque. Firstly, the equations of the stator and rotor fluxes should be considered:

\[ \tilde{\psi}_s = L_s \tilde{i}_s + L_m \tilde{i}_r \]  
\[ \tilde{\psi}_r = L_r \tilde{i}_r + L_m \tilde{i}_s \]  

Both are referred again to the stationary reference frame fixed to the stator. If the stator and rotor currents are isolated, then:

\[ \tilde{i}_s = \frac{\tilde{\psi}_s}{L_s} - \frac{L_m}{L_s} \tilde{i}_r \]  
\[ \tilde{i}_r = \frac{\tilde{\psi}_r}{L_r} - \frac{L_m}{L_r} \tilde{i}_s \]  

Substituting the rotor current expression into the stator current expression, the next equation is obtained:

\[ \tilde{i}_s = \frac{\tilde{\psi}_s}{L_s} - \frac{L_m}{L_s} \left( \tilde{\psi}_r - L_m \tilde{i}_s \right) \]  

And isolating the stator current again,

\[ \tilde{i}_s = \frac{L_r}{L_r - L_m} \tilde{\psi}_s - \frac{L_m}{L_r - L_m} \tilde{\psi}_r \]  

Finally substituting the previous expression (6) into the equation (1), the following new expressions for the electromagnetic torque are obtained:

\[ t_e = \frac{3}{2} P \frac{L_m}{L_r - L_m} \tilde{\psi}_r \times \tilde{\psi}_s \]  

Finally, the torque expression is as follows:

\[ t_e = \frac{3}{2} \frac{L_m}{L_r - L_m} \tilde{\psi}_r \times \tilde{\psi}_r \cdot \sin(\rho_s - \rho_r) \]  

Because of the rotor time constant is larger than the stator one, the rotor flux changes slowly compared to the stator flux; in fact, the rotor flux can be assumed constant. (The fact that the rotor flux can be assumed constant is true as long as the response time of the control is much faster than the rotor time constant, which is usually between 0.04 and 0.1s). As long as the stator flux will be kept constant, then the electromagnetic torque can be rapidly changed and controlled by means of changing the angle \( \rho_s - \rho_r \).[1][3].

2.3 - DTC Controller: 
The way to impose the required stator flux is by means of the Voltage Source Inverter state. If the ohmic drops are neglected for simplicity, then the stator voltage impresses directly the stator flux in accordance with the next equation:

\[ \frac{d\tilde{\psi}_s}{dt} = \tilde{u}_s \]  

Or:

\[ \Delta \tilde{\psi}_s = \tilde{u}_s \Delta t \]  

Decoupled control of the torque and stator flux is achieved by acting on the radial and tangential components of the stator flux-linkage space vector in its locus. These two components are directly proportional (Rs=0) to the components of the same voltage space vector in the same directions.

Next figure 1 shows the possible dynamic locus of the stator flux, and its different variation depending on the VSI states chosen. The possible global locus is divided into six different sectors signalled by the discontinuous line.
In Accordance with the figure 1, the following general table can be written:

<table>
<thead>
<tr>
<th>IN THE k SECTOR</th>
<th>INCREASE</th>
<th>DECREASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator Flux</td>
<td>K,k+1,k-1</td>
<td>k+2,k-2,k+3</td>
</tr>
<tr>
<td>Torque</td>
<td>K+1,k+2</td>
<td>k-1,k-2</td>
</tr>
</tbody>
</table>

Table I: General Selection Table for Direct Torque Control.

It can be seen that the states k and k+3, are not considered in the Torque because they can both increase or decrease the torque at the same sector depending on if the position is in the first 30 degrees or in the second ones. The usage of these states for controlling the Torque is considered one of the points to develop in the further research dividing the total locus into twelve sectors instead of just six .

Finally, if the table is developed can be obtained the following one:

<table>
<thead>
<tr>
<th>Φ</th>
<th>τ</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>1</td>
<td>V2</td>
<td>V3</td>
<td>V4</td>
<td>V5</td>
<td>V6</td>
<td>V1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>V0</td>
<td>V7</td>
<td>V0</td>
<td>V0</td>
<td>V7</td>
<td>V7</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>V6</td>
<td>V1</td>
<td>V2</td>
<td>V3</td>
<td>V4</td>
<td>V5</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>V3</td>
<td>V4</td>
<td>V5</td>
<td>V6</td>
<td>V1</td>
<td>V2</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>V7</td>
<td>V0</td>
<td>V7</td>
<td>V0</td>
<td>V7</td>
<td>V0</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>V5</td>
<td>V6</td>
<td>V1</td>
<td>V2</td>
<td>V3</td>
<td>V4</td>
</tr>
</tbody>
</table>

Table II: Selection Table for Direct Torque Control

The sections of the stator flux space vector are denoted from S1 to S6. The flux error (Φ), as it is explained in the following paragraph, can take two different values, meanwhile the torque error (τ) can take three different values. The zero voltage vectors  

$V_6$ and $V_7$ are selected when the torque error is within the given hysteresis limits.

### 2.4 - DTC Control Schematic:

In figure 2 a possible schematic of Direct Torque Control is shown. As it can be seen there are two different loops corresponding to the magnitudes of the stator flux and torque. The reference values for the flux stator and the torque are compared with the actual values, and the resulting values are fed into the two-level and three-level hysteresis comparators respectively. The outputs of the stator flux (Φ) and torque (τ) comparators with the position of the stator flux are used as inputs of the look up table (see table II). The position of the stator flux is divided into six different sections. In accordance with the figure 2, the flux linkage and torque errors are restricted within its respective hysteresis bands. It can be proved that the flux hysteresis band affects basically to the stator-current distortion in terms of low order harmonics and the torque hysteresis band affects the switching frequency.

The DTC requires the flux and torque estimations, which can be performed as it is proposed in the schematic 2, by means of two different phase currents and the state of the inverter.

The flux and torque estimations can be performed by means of other estimators using other magnitudes such as two stator currents and the mechanical speed, or two stator currents again and the shaft position.

### 3. Conclusions

Provided that in Europe the electrical drives business is worth approximately $1.0 Billion/ Annum and induction motors are the new horsepower of the industry, it is obvious that the improvement in the induction motors drives is a matter of high interest.

Direct Torque Control is considered to be one of the best methods to drive induction motors, even better that the well-known Vector Controls. However, DTC has some disadvantages, being one of the most important the torque ripple. Further research must be
focused on trying to improve this main DTC disadvantage by means of artificial intelligence methods.

References

