Experimental Implementation of PI and Fuzzy based DTC with Performance Analysis

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Abstract – This paper presents an experimental study of a well-known control strategy of induction machine (IM); i.e Direct Torque control (DTC). Proportional+Integral (PI) and Fuzzy Logic (FLC) controllers are used in speed regulation loop, and comparison is achieved. The use of optimized FLC has good benefit on the performance of the control system.

A common hardware platform is realized, and a series of tests are conducted to emphasize the relative advantages and disadvantages of each method. The Experimental test bench is carried out under Matlab/Simulink with real time interface (RTI) and the dSpace (DS1104) board.

Keywords – DTC, Induction Motor, Fuzzy Logic, dSPACE

I. INTRODUCTION

The induction motor has a major advantage compared to other types of motor (DC, synchronous,). It’s the robustness and low cost of manufacturing and free maintenance. To preserve this superiority, it was necessary to develop a drives to control the speed as well as it was possible to do with other types of machines such as DC, and synchronous motors.

Since they have been invented in the late of 1960’s and middle of 1980’s respectively, the FOC [1] and DTC [2,3], are until nowadays the most privileged techniques when high performances control are required.

Compared with the Rotor field oriented control, the DTC has many advantages such as less machine parameter dependence, intrinsically speed sensorless, simpler implementation and quicker dynamic torque response, with no need of currents controllers neither a coordinate transforms. But it suffers of current's oscillations, torque ripples and variable switching frequency. In counterpart the FOC presents good dynamic, more stability at steady state, low switching frequency and less currents and torque ripples, but it major drawbacks are; more computation time (needed in Park’s transformation, and decoupling), more sensitive to parametric variations, several controllers loops and requires a speed sensor [4].

Taking into mind the industrial interest of these two major techniques, many researchers have taken the task to compare them by simulation and experiment, but each of authors had its own visions and aims. The most popular papers are [5-15]. The summarized comparison results presented that the DTC has many advantages such as less machine parameter dependence, intrinsically speed sensorless, simpler implementation and quicker dynamic torque response, with no need of currents controllers neither a coordinate transforms. But it suffers of current's oscillations, torque ripples and variable switching frequency. In counterpart the FOC presents good dynamic, more stability at steady state, low switching frequency and less currents and torque ripples, but it major drawbacks are; more computation time (needed in Park’s transformation, and decoupling), more sensitive to parametric variations, several controllers loops and requires a speed sensor.

Many drive systems employ a conventional controller such as a PI type controller, which, well-known works perfectly but only under a certain conditions like unchanged system parameters or load conditions, otherwise the performance of the closed loop system will be deteriorated, resulting in an unstable system. Thus, the need for other type of controllers, which can account for nonlinearity or somewhat adaptable to varying, conditions in real time.
without the need for operator reprogramming. Other controllers are now being employed such as fuzzy in order to achieve a desired performance level. Fuzzy logic controllers (FLC) have been proved to be successfully used for a number of complex and nonlinear processes, with more robustness and less sensitive to parametric variations than conventional controllers. A lot of researchers in the domain of IM drive pay attention to the design and implementation of FLC, it can be found in [16-20].

In this work, we have chosen to study the DTC strategy. And we wanted to contribute to these works by adding an experimental comparison investigation to the literature. The selected criteria to evaluate their performances are studied in both steady-state and transient operating conditions when using a PI and FLC speed controllers. Thus, this paper is organized as follows; the IM model and the DTC details are given at section II, the fuzzy logic control description is discussed at section III. The experimental results and discuss are presented at section IV.

II. IM MODE AND DTC DESCRIPTION

A. Induction Motor Model

The dynamic model of three-phase, Y-connected induction motor can be expressed in the d-q synchronously rotating frame as:

\[
\begin{align*}
\frac{di_d}{dt} &= -a_1i_d + \omega_c i_q + a_2\psi_r + a_3\omega C\psi_r + a_0v_s \\
\frac{di_q}{dt} &= a_5i_d - a_4\psi_r + \omega 2\psi_r
\end{align*}
\]

Where \(i = [i_{sd}, i_{sq}]^T\), \(\psi_r = [\psi_{rth}, \psi_{rth}]^T\), and \(v_s = [v_{sph}, v_{slh}]^T\) are respectively the vectors of stator currents, rotor flux linkages, and stator voltages. \(\omega_c\) is the synchronously rotating angular speed, \(\omega\) is the electrical angular speed of the rotor, and \(\omega_s = \omega - \omega\) is the slip frequency. And:

\[
\begin{align*}
a_0 &= 1/\sigma L_z, a_1 = a_0(R_z + R_r L_m^2/L_r^2), a_2 = a_0R_r L_m/L_r, a_3 = a_4L_m, a_5 = -a_5
\end{align*}
\]

Where \(R_z\) and \(R_r\) are the stator and rotor resistances, \(L_z\) and \(L_r\) are the stator and rotor inductances, \(L_m\) is the mutual inductance between the stator and the rotor winding, \(\sigma = 1 - (L_m^2/L_z L_r)\) is the total leakage factor. The electromagnetic torque \(T_e\) can be expressed in terms of stator currents and rotor flux linkages as:

\[
T_e = \frac{3}{2} \eta L_r \left(\psi_{r2}i_{2q} - \psi_{r2}i_{2d}\right)
\]

Where: \(\eta\) is pole pair number.

The motional equation of IM is described as:

\[
J\Omega = T_e - T_L - f_v\Omega
\]

Where \(J\) is the moment of inertia, \(T_L\) is the load torque, \(f_v\) is the viscous friction coefficient, and \(\Omega = \omega/p\) is the mechanical motor speed, and \((\cdot)\) is the derivative. The position is expressed as:

\[
\theta_s = \int \omega_s dt
\]
B. DTC Theory

The term direct control of torque and flux is based on the fact that from the errors between the reference values of the torque (and the flux) and those estimated, it is possible if we know the flux angle (thus the sectors) to directly control the states of the voltage source inverter (VSI) to reduce errors within hysteresis controllers as shown on Fig. 1.

The IM is fed by a current-controlled PWM inverter, the speed control loop uses a PI or FLC controller to produce the motor torque reference $T_e^*$ which gives the quadrature-axis current reference $i_{sq}^*$.

![DTC Schematic](image)

**Fig. 1 Shematic of the DTC**

The DTC development is carried out on the stationary reference fame ($\alpha,\beta$), the electrical equations of IM are then:

$$
\begin{align*}
\dot{v}_s &= R_s i_s + \frac{d\psi}{dt} \\
0 &= R_r i_r + \frac{d\psi_r}{dt} - j \omega \psi_r
\end{align*}
$$

(5)

Where $i_s=[i_{sa}, i_{sb}]$, $\psi_s=[\psi_{sa}, \psi_{sb}]$, $\psi_r=[\psi_{ra}, \psi_{rb}]$, $v_s=[v_{sa}, v_{sb}]$ are respectively the vectors of; stator currents, stator/rotor flux linkages, and stator voltages.

Stator- flux components are estimated by:

$$
\psi_s = \int (v_s - R_s i_s) \, dt
$$

(6)

Modulus and angle of flux can be obtained as follows:
\[
|\psi_s| = \sqrt{\psi_{sa}^2 + \psi_{sb}^2} \\
\theta_s = \tan^{-1}\left(\frac{\psi_{sb}}{\psi_{sa}}\right)
\]  

(7)

Thus, the electromagnetic torque can be estimated via the stator flux and currents:

\[
T_e = p(\psi_{sa}i_{sb} - \psi_{sb}i_{sa})
\]  

(8)

As afore mentioned, the DTC is based on the use of two hysteresis controllers, these evaluate the difference between requested values and estimated values, and thereby determine if the flux and torque vectors should be increased, decreased, or constant. It is proved that the band width of the flux hysteresis comparator has influence on current distortion (harmonics), while torque ripples and switching frequency of the VSI device are affected by torque hysteresis band [4].

A logic signals are produced from the switching table and used to trigger the switches of the three-phase VSI. There are six possible active combinations of these logic signals with the corresponding active input voltage vectors of the inverter depending on sector number, as shown in Fig. 1.

III. FUZZY LOGIC SPEED CONTROLLER (FLC)

In our work the FLC was designed using the Fuzzy Control Toolbox provided within Matlab, with the Mamdani’s min-max decision inference engine.

Error \(e(k)\) and change in speed error signals \(de(k)\) are used as the inputs of the speed controller, and one output is taken to provide the torque command. Then they are multiplied by the respective scale factors to adjust the fuzzy domain \([-1, 1]\), we conclude from experimentation that, these scaling factors play a fundamental role for the stability, oscillations and damping of the system. For each value of error, error change and torque, the degree of membership (\(\mu\)) is evaluated for all the membership functions as illustrated at Fig. 2, and associated with the fuzzy variable which consists of five fuzzy sets; positive large (PL) and negative large (NL) which are represented by triangular membership functions (mf); positive small (PS), zero (ZE), and negative Small (NS), and positive large (PL).

These lead to 25 control rules of IF ... THEN, structured as given in Table I.

<table>
<thead>
<tr>
<th>(e(k))</th>
<th>(de(k))</th>
<th>NL</th>
<th>NS</th>
<th>ZE</th>
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<tr>
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Figure 1. Membership distribution of inputs and output.
Fig. 2 Membership distribution of inputs and output

Then, inferred fuzzy control action is converted to a crisp value ($T_e^*$), through the center of gravity defuzzification method.

IV. EXPERIMENT IMPLEMENTATION AND RESULTS

A three phase Y connected; 1kW, 2880rpm, 230/400V, 4/2.8A, squirrel cage IM is tested to achieve the comparison. The IM parameters were identified through the standard tests and are given on appendix. The IM is loaded via 1kW DC generator, and coupled to a 1024pt incremental encoder for speed measurement. The control system is implemented on dSpace DS1104 board with the help of Matlab/Simulink (RTI) blocks. Fig. 3 shows the hardware snapshot of the experimental setup. Through the ControlDesk software a control panel has been developed (Fig. 4); it provides an easy handling interface between dSPACE and Simulink blocks, and useful tool for online variation of the operating parameters of the system.

Fig. 3 Snapshot of the hardware setup
A. Performance Analysis and Comparison

The performances of the PI regulated speed method (DTC-PI) and when intelligent controller (i.e. fuzzy controller) is introduced in speed control loop (DTC-FLC) are examined. The sampling periods in DTC-PI is set to $T_s = 100 \mu s$. It is noted that the sampling period for DTC-FLC was increased up to $T_s = 600 \mu s$, because the algorithm requires more calculating time and we have got an "over-run" during compilation from simulink to dSpace, unfortunately this is the main limitation of the DS1104. The values of the PI gains regulators are; $K_p = 0.13$, $K_i = 0.001$, we should note that these values are different from those calculated by the well known methods (because the drives did not worked), this is certainly due to the measure uncertainties and simplifying assumptions at the parameters identification, we were have to adjust them online from the ControlDesk control panel. The FLC scaling factors are; $K_e = 0.1$, $K_{de} = 0.001$, $K_{Te} = 1$.

Figs. 5-6 show the DTC results with PI regulators (on the left side) when IM is operating at high and low speed. Starting with 50% of load disturbance, and following with sharp changes to 0% and up to 100% of nominal load torque respectively. For DTC-FLC (on the right side) the torque transients is observed when the machine was subjected to a series of torque changes, starting with 10% and up to 50% of nominal torque.

It can be compared that, in the steady state, the torque ripple in the DTC-PI is less than in DTC-FLC. However, both schemes achieve high dynamic performance in response to changes in torque demand. The DTC-FLC presents good dynamics and disturbance rejection with no overshoot. And the flux has hexagonal form.
This is mainly due to the large sampling period. It is seen that DTC-PI presents significant overshoot and slow disturbance rejection with steady state error, but the flux follows a circular trajectory.

At low speed the motor is following a command 0 rpm and 500 rpm, both schemes present good response time (Figs. 7), but we note the well-known low speed problem in DTC which presents speed and torque ripples approximately 0.5N.m, this led acoustic noises and
vibrations. A significant superiority of DTC-FLC upon the DTC is observed in settling time and disturbance rejection.

We can conclude that the speed tracking performance of DTC-FLC has become more efficient with respect to the DTC with PI control.

B. More Performance Analysis

We added tests of robustness to sudden changes in speed reference with reversal when IM is operating at half load capacitance.

![Fig. 7 Low speed performance PI (left), FLC (right), with multiple torque command](image1)

![Fig. 8 PI (left), FLC (right), based DTC behavior at sharp speed command](image2)
From Fig. 8, which gives the speed tracking evolution; we can see that the DTC-FLC presents fast response and less oscillation. During acceleration mode the motor delivers full torque until the speed reaches its requested reference, the torque then drops to the same value as the load’s torque to keep the speed constant. In DTC-PI the electromagnetic torque presents more ripples.

On Fig. 9, one can observe the behavior when trapezoidal speed command is introduced and the IM is started at 50% with sudden change to 0% and so on, of nominal load is applied. Despite of good speed tracking and fast torque response, the performance of the control is still affected by the ripples for both schemes; additionaly; we can remark the steady state error in DTC-FLC.

C. Optimization of the FLC Control

The apparent degradations of the FLC method due to the sampling time led us to optimize the number of MFs, and thus the rules. This will lead to less computation time which will allow the reduction of the sampling time $T_s$ of the real-time implementation. The same fuzzy caracteristic design are used, the shapes of the MFs and rules are presented on Fig. 10, and Table 2, respectively.

By adopting this approach, the sampling period was reduced to $T_s=230\mu s$. The results are shown on Figs.11-13.

As illustrated, by using the optimized FLC, the system control became increasingly efficient in term of speed tracking and disturbance rejection, with significantly less ripples in torque response and circular flux trajectory.
Fig. 10 Membership shapes of inputs and output.

### TABLE II. LINGUISTIC RULE TABLE

<table>
<thead>
<tr>
<th>$de(k)$</th>
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Fig. 11 Optimized FLC based DTC behavior at start-up and high speed

On Fig. 13, IM is operating at full load, the measured speed follow its command perfectly and no steady state error is observed. The system achieve less ripples and the flux path is circular.

V. CONCLUSION

Introduction of a fuzzy approach in DTC control has demonstrated; fast speed response, rapid load disturbance rejection with respect to conventional PI controllers. The experimental
results have shown the interest of the optimization approach which has a direct influence on ripples, and overall system stability.

![Graphs](image1.png)

Fig. 12 Optimized FLC based DTC behavior at start-up and low speed command (at left), and Multi-steps command (at right).

![Graphs](image2.png)

Fig. 13 Optimized DTC-FLC based behavior at trapezoidal speed command.

**APPENDIX**

Poles : 2  
\( R_s = 6.58\,\Omega, R_r = 5.81\,\Omega \)  
\( L_s = 0.749\,\text{H}, L_r = 0.749\,\text{H}, L_m = 0.7209\,\text{H} \)  
Inertia constant : 0.00207 kg.m²  
Viscous constant : 0.000173 kg.m/s
REFERENCES


