Direct Torque Control Strategy Based on Fuzzy Logic Controller for a Doubly Fed Induction Motor

N El Ouanjli¹, A Derouich¹, A El Ghzizal¹, A Chebabhi², M Taoussi³, B Bossoufi³,⁴

¹ Laboratory of Production Engineering, Energy and Sustainable Development, the Higher School of Technology, Sidi Mohamed Ben Abdellah University Fez, Morocco.
² Faculty of Sciences and Technology, University of Bordj Bou Arreridj, Algeria.
³ Laboratory of Systems Integration and Advanced Technologies, Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdellah University Fez, Morocco.
⁴ Laboratory of Electrical Engineering and Maintenance, ESTO School of Technology, University Mohammed I Oujda, Morocco

E-mail: najib.elouanjli@usmba.ac.ma

Abstract. In this paper, we are interested in the study and improvement of the performances of a Doubly Fed Induction Machine (DFIM) functioning in motor mode using the strategy of Direct Control Torque (DTC) based on fuzzy logic. At first, we are focusing in the study of the functioning principle and the modeling of the DFIM. Secondly, we applied the fuzzy approach to the DTC control. Finally, the simulation results of the control are validated on the Matlab/Simulink environment followed by a detailed analysis.

1. Introduction

For few years, various control strategies have been developed in order to carry out a decoupled control of the doubly fed induction machine. These methods called "vector controls" provide dynamic performance equivalent to that obtained by the direct current machine [1] [2]. Today, the development of new digital signal processing techniques has led to much more sophisticated control strategies. The most recent steps in this direction are those grouped under the term direct torque control [3].

The direct torque control, which is based on the direct regulation of the flux and the electromagnetic torque of the machine [4], has been the most important research and best adapted to industrial requirements, it is characterized by good stability, precision, a good torque response, robustness and less complexity than other controls [5].

Our objective consists in improving the DTC control, by reducing the ripples of the flows and torque by an intelligent technique based on fuzzy logic, the algorithm of this control is based on the use of two fuzzy tables which replace the hysteresis comparators and the conventional tables [6] [7]. we have checked this control strategy by simulation in Matlab / simulink, it remains the validation by the tests PIL as the works [8]. This article is organized as follows: The first part will be devoted to the modeling of the doubly fed induction machine and the two-level voltage inverter. The second part concerns with the fuzzy DTC control of this machine. In a third part and in order to validate our model, simulation results curves using the Matlab/Simulink software will be presented and analysed.
2. Modeling of the system
The power supply of the doubly fed induction machine operating in motor mode and variable speed is assured by two voltage converters which are reciprocally connected to the stator and rotor windings [9].

Figure 1. Overall scheme of the system studied

2.1. Modeling of the DFIM
Before doing the modeling of a doubly fed induction machine, it is necessary to represent a two-phase model (d, q) given by Park transformation [10].

The model of the doubly fed induction machine after the Park transformation is defined by the electrical, magnetic and mechanical following equations [11].

2.1.1. Electrical equations
The equations of the stator and rotor voltages $V_{s,r}(d,q)$ in the reference (d,q), are expressed by:

$$
\begin{align*}
V_{sd} &= R_s i_{sd} + \frac{d\psi_{sd}}{dt} - \omega_s \psi_{sq} \\
V_{sq} &= R_s i_{sq} + \frac{d\psi_{sq}}{dt} + \omega_s \psi_{sd} \\
V_{rd} &= R_r i_{rd} + \frac{d\psi_{rd}}{dt} - \omega_r \psi_{rq} \\
V_{rq} &= R_r i_{rq} + \frac{d\psi_{rq}}{dt} + \omega_r \psi_{rd}
\end{align*}
$$

(1)

2.1.2. Magnetic equations
The stator and rotor flux are expressed by:

$$
\begin{align*}
\psi_{sd} &= L_s i_{sd} + M_{sr} i_{rd} \\
\psi_{sq} &= L_s i_{sq} + M_{sr} i_{rq} \\
\psi_{rd} &= L_r i_{rd} + M_{sr} i_{sd} \\
\psi_{rq} &= L_r i_{rq} + M_{sr} i_{sq}
\end{align*}
$$

(2)

2.1.3. Mechanical equation
The mechanical equation is given by:

$$
T_{em} = T_r + f. \frac{d\Omega}{dt} + f. \Omega
$$

(3)

The expression of electromagnetic torque based on rotor flux and currents is given, by:

$$
T_{em} = p. (\psi_{rq} i_{rd} - \psi_{rd} i_{rq})
$$

(4)
With:

\[ V_{s(d,q)}, V_{r(d,q)}: \text{Stator and rotor voltages in the Park reference.} \]
\[ I_{s(d,q)}, I_{r(d,q)}: \text{Stator and rotor currents in the Park reference.} \]
\[ \psi_{s(d,q)}, \psi_{r(d,q)}: \text{Stator and rotor flux in the Park reference.} \]
\[ R_s, R_r: \text{Stator and rotor resistances.} \]
\[ L_s, L_r, M: \text{Stator, rotor and mutual inductances.} \]
\[ \omega_s, \omega_r: \text{Stator and rotor pulsations.} \]
\[ T_r: \text{Load and electromagnetic torque.} \]
\[ T_{em}: \text{Electromagnetic torque.} \]
\[ P: \text{Pole pair number.} \]
\[ J: \text{Moment of inertia.} \]
\[ f: \text{Coefficient of viscous friction.} \]

2.2. Modeling of the inverter

The mathematical model of the two-level inverter is represented by the following matrix [12]:

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} = \frac{1}{3} U_c \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix}
\] (5)

The state of switches, assumed to be perfect, can be represented by three Boolean magnitude of control \( S_i (i=a, b, c) \), such as:

- \( S_i = 1 \) if \( T_j \) (\( i=1,2,3 \)) is closed and \( T_k \) (\( j=4,5,6 \)) is open.
- \( S_i = 0 \) if \( T_j \) (\( i=1,2,3 \)) is open and \( T_k \) (\( j=4,5,6 \)) is closed.

3. Direct Torque Control based on the Fuzzy Logic

3.1. Principle of the direct torque control

The direct torque control consists in directly controlling the flows and the electromagnetic torque of the doubly fed induction machine by the use of two switching tables whose functions are the direct determination of the control sequences applied to the switches of the voltage inverters [13].

The expression of the inverter voltage vector can be given in the form below:

\[
V = \left[ \frac{2}{3} U_c (S_a + S_b e^{j\frac{2\pi}{3}} + S_c e^{j\frac{4\pi}{3}}) \right]
\] (6)

With:

\[ S_a, S_b, S_c: \text{Switching logic states (0 or 1).} \]
\[ U_c: \text{DC bus voltage.} \]

The set of voltage vectors delivered by each inverter of voltage at two levels are represented in the following figure:

\[ \text{Figure 2. Voltage vectors delivered by the voltage inverter} \]

Direct torque control is also based on the estimation of the stator flux, rotor flux and electromagnetic torque of the machine [14], the module of the stator and rotor flux is written:
\[ \hat{\psi}_s = \sqrt{\hat{\psi}_{s\alpha}^2 + \hat{\psi}_{s\beta}^2} \quad \text{and} \quad \hat{\psi}_r = \sqrt{\hat{\psi}_{r\alpha}^2 + \hat{\psi}_{r\beta}^2} \] 

(7)

With: \( \psi_{s\alpha}, \psi_{s\beta}, \psi_{r\alpha} \) and \( \psi_{r\beta} \) are of the stator and rotor flux in the reference frame \((\alpha,\beta)\).

The position of the flux vectors calculated as follows:

\[ \theta_s = \arctg\left( \frac{\hat{\psi}_{s\beta}}{\hat{\psi}_{s\alpha}} \right) \quad \text{and} \quad \theta_r = \arctg\left( \frac{\hat{\psi}_{r\beta}}{\hat{\psi}_{r\alpha}} \right) \] 

(8)

The electromagnetic torque is estimated from the measured rotor currents:

\[ T_{\text{em}} = p. (\dot{\psi}_{r\alpha} \cdot i_{r\beta} - \dot{\psi}_{r\beta} \cdot i_{r\alpha}) \] 

(9)

3.2. DTC control based on the fuzzy logic

To improve the performances of the system and to minimize ripples in the electromagnetic torque and flux, two fuzzy logic controllers presented to replace the controllers of hysteresis and the conventional switching tables [15]. In this system there are three inputs for the fuzzy logic controller, which are flux angle, torque error and flux error [16].

\[ \theta_s = \arctg\left( \frac{\hat{\psi}_{s\beta}}{\hat{\psi}_{s\alpha}} \right) \quad \text{and} \quad \theta_r = \arctg\left( \frac{\hat{\psi}_{r\beta}}{\hat{\psi}_{r\alpha}} \right) \] 

(10)

\[ \varepsilon_{T_{\text{em}}} = (T_{\text{em}})_{\text{ref}} - \hat{T}_{\text{em}} = \Delta T_{\text{em}} \] 

(11)

\[ \varepsilon_{\psi_s} = (\dot{\psi}_{s})_{\text{ref}} - \dot{\psi}_s = \Delta \psi_s \] 

(12)

\[ \varepsilon_{\psi_r} = (\dot{\psi}_{r})_{\text{ref}} - \dot{\psi}_r = \Delta \psi_r \] 

(13)

The figure 3 bellow gives the block diagram adopted for fuzzy-DTC control of the doubly fed induction machine:

**Figure 3.** Synoptic schema of the fuzzy DTC applied to DFIM
The switching table at the stator side by the fuzzy logic is illustrated in the following figure 4, (the same reasoning for the rotor side):

![Figure 4. switching table by fuzzy logic](image)

The universe of discourse of the flux position (stator flux or rotor flow) is divided into six fuzzy sets ($\theta_1$ to $\theta_6$). We choose the triangular membership function for all angles $\theta_i$.

![Figure 5. Membership function for flux position](image)

The universe of discourse of the electromagnetic torque error is divided into three fuzzy sets (torque error is positive (P); torque error is zero (Z) and torque error is negative (N)). We choose the triangular membership function for the fuzzy set (Z). And the trapezoid membership functions for the fuzzy sets (P) and (N).

![Figure 6. Membership function for error of the electromagnetic torque](image)

The universe of discourse of the flux error is divided into two fuzzy sets (flux error is positive (P); flux error is negative (N)). We choose the trapezoid membership functions for the two fuzzy sets.

![Figure 7. Membership function for flux error](image)
The output variable is decomposed into three sub-outputs representing three switching magnitudes $(S_a, S_b, S_c)$ of switches of the inverter at two levels, the universe of discourse of each output is divided into two fuzzy sets (zero and one) whose membership functions are chosen by trapezoid forms.

![Membership functions for output variables](image)

**Figure 8. Membership functions for output variables**

The fuzzy rules base with 36 rules can be obtained from the following table 1.

| $e_{\phi}$ | $e_{T_{em}}$ | $\theta_1$ | $\theta_2$ | $\theta_3$ | $\theta_4$ | $\theta_5$ | $\theta_6$ |
|-----------|--------------|------------|------------|------------|------------|------------|------------|
| N         | N            | v6         | v1         | v2         | v3         | v4         | v5         |
| N         | Z            | v7         | v0         | v7         | v0         | v7         | v0         |
| N         | P            | v2         | v3         | v4         | v5         | v6         | v1         |
| P         | N            | v5         | v6         | v1         | v2         | v3         | v4         |
| P         | Z            | v0         | v7         | v0         | v7         | v0         | v7         |
| P         | P            | v3         | v4         | v5         | v6         | v1         | v2         |

**Table 1. Set of fuzzy rules**

4. Simulation results

In order to show the performance and robustness of the fuzzy DTC control of DFIM, we simulated the dynamic behavior of DFIM in the Matlab/Simulink environment.

The following figures show the behavior of the structure of the direct torque control by the fuzzy logic applied to the doubly fed induction machine of 1.5 kW.

**Figure 9. Rotation speed**

**Figure 10. Electromagnetic torque**

**Figure 11. Stator flux**

**Figure 12. Rotor flux**
Figure 13. Evolution of the stator flux  
Figure 14. Evolution of the rotor flux  

According to the simulation results, it is found that the speed and the electromagnetic torque reached its reference values with a fast response time ($t_r=0.3$ s). The stator and rotor flux remain constant at their reference values whatever the applied load which shows that the torque and the flux are decoupled. The evolution of these flows in the reference frame ($\alpha$, $\beta$) is perfectly circular. We also note that the electromagnetic torque and flows of the machine present less undulation compared to other classic commands. The results obtained show efficiency of the chosen algorithm for improving performances and for minimizing ripples of the torque and flux of the machine.

5. Conclusion  
The objective of this work consists in the modeling, the development and the simulation of the fuzzy DTC control for a doubly fed induction machine powered by two voltage converters. The simulation results clearly show that the system perfectly follows the reference values and that the control approach studied provides a very interesting solution to the problems encountered in to other classic controls. To continue and to complete this work, we will test and implement this control law by using a test bench based on an FPGA target in the laboratory.

Appendix  

Table 2. Parameters of the DFIM

| Variable                      | Symbol | Value (unit) |
|-------------------------------|--------|--------------|
| Nominal power                 | $P_m$  | 1.5 kW       |
| Stator nominal voltage        | $V_{sn}$ | 230 V       |
| Rototor nominal voltage       | $V_{rm}$ | 130 V       |
| Frequency                     | $f$    | 50 Hz        |
| Pair pole number              | $P$    | 2            |
| Stator self inductance        | $L_s$  | 0.295 H      |
| Rotor self inductance         | $L_r$  | 0.104 H      |
| Maximum of mutual inductance  | $M$    | 0.165 H      |
| Stator resistance             | $R_s$  | 1.75 $\Omega$ |
| Rotor resistance              | $R_r$  | 1.68 $\Omega$ |
| Total viscous frictions       | $f$    | 0.0027 Kg.m²/s |
| Total inertia                 | $J$    | 0.01 Kg.m²   |

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