

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

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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].

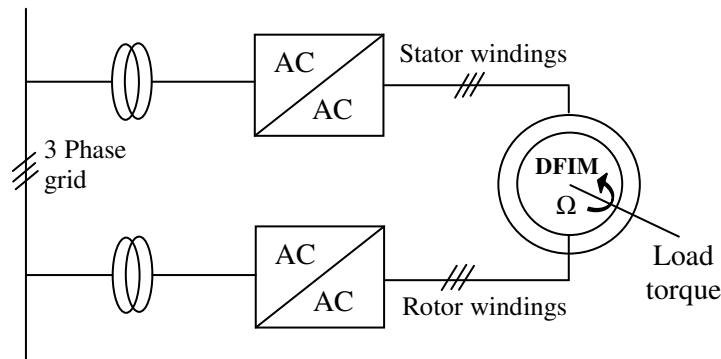


Figure 1. Overall scheme of the system studied

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:

$$\begin{cases} V_{sd} = R_s \cdot i_{sd} + \frac{d\psi_{sd}}{dt} - \omega_s \cdot \psi_{sq} \\ V_{sq} = R_s \cdot i_{sq} + \frac{d\psi_{sq}}{dt} + \omega_s \cdot \psi_{sd} \\ V_{rd} = R_r \cdot i_{rd} + \frac{d\psi_{rd}}{dt} - \omega_r \cdot \psi_{rq} \\ V_{rq} = R_r \cdot i_{rq} + \frac{d\psi_{rq}}{dt} + \omega_r \cdot \psi_{rd} \end{cases} \quad (1)$$

2.1.2. Magnetic equations

The stator and rotor flux are expressed by:

$$\begin{cases} \psi_{sd} = L_s \cdot i_{sd} + M_{sr} \cdot i_{rd} \\ \psi_{sq} = L_s \cdot i_{sq} + M_{sr} \cdot i_{rq} \\ \psi_{rd} = L_r \cdot i_{rd} + M_{sr} \cdot i_{sd} \\ \psi_{rq} = L_r \cdot i_{rq} + M_{sr} \cdot i_{sq} \end{cases} \quad (2)$$

2.1.3. Mechanical equation

The mechanical equation is given by:

$$T_{em} = T_r + J \cdot \frac{d\Omega}{dt} + f \cdot \Omega \quad (3)$$

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

$$T_{em} = p \cdot (\psi_{rq} \cdot i_{rd} - \psi_{rd} \cdot i_{rq}) \quad (4)$$

With:

- $V_{s(d,q)}, V_{r(d,q)}$: Stator and rotor voltages in the Park reference.
 $I_{s(d,q)}, I_{r(d,q)}$: Stator and rotor currents in the Park reference.
 $\psi_{s(d,q)}, \psi_{r(d,q)}$: Stator and rotor flux in the Park reference.
 R_s, R_r : Stator and rotor resistances.
 L_s, L_r, M : Stator, rotor and mutual inductances.
 ω_s, ω_r : Stator and rotor pulsations.
 T_r : Load and electromagnetic torque.
 T_{em} : Electromagnetic torque.
 P : Pole pair number.
 Ω : Rotation speed of the machine.
 J : Moment of inertia.
 f : 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]:

$$\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = \frac{1}{3} U_c \cdot \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \cdot \begin{pmatrix} S_a \\ S_b \\ S_c \end{pmatrix} \quad (5)$$

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:

$$V = \sqrt{\frac{2}{3}} U_c (S_a + S_b e^{\frac{j2\pi}{3}} + S_c e^{\frac{j4\pi}{3}}) \quad (6)$$

With:

- S_a, S_b, S_c : Switching logic states (0 or 1).
 U_c : DC bus voltage.

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

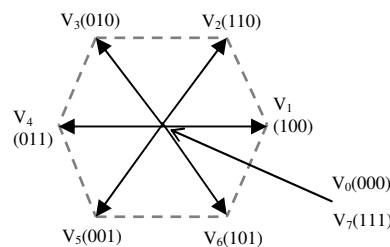


Figure 2. Voltage vectors delivered by the voltage inverter

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:

$$\hat{\psi}_s = \sqrt{\hat{\psi}_{s\alpha}^2 + \hat{\psi}_{s\beta}^2} \text{ and } \hat{\psi}_r = \sqrt{\hat{\psi}_{r\alpha}^2 + \hat{\psi}_{r\beta}^2} \quad (7)$$

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 (α, β).
The position of the flux vectors calculated as follows:

$$\theta_s = \arctg\left(\frac{\hat{\psi}_{s\beta}}{\hat{\psi}_{s\alpha}}\right) \text{ and } \theta_r = \arctg\left(\frac{\hat{\psi}_{r\beta}}{\hat{\psi}_{r\alpha}}\right) \quad (8)$$

The electromagnetic torque is estimated from the measured rotor currents:

$$\hat{T}_{em} = p \cdot (\hat{\psi}_{r\alpha} \cdot i_{r\beta} - \hat{\psi}_{r\beta} \cdot i_{r\alpha}) \quad (9)$$

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].

$$\theta_s = \arctg\left(\frac{\hat{\psi}_{s\beta}}{\hat{\psi}_{s\alpha}}\right) \text{ and } \theta_r = \arctg\left(\frac{\hat{\psi}_{r\beta}}{\hat{\psi}_{r\alpha}}\right) \quad (10)$$

$$\varepsilon_{T_{em}} = (T_{em})_{ref} - \hat{T}_{em} = \Delta T_{em} \quad (11)$$

$$\varepsilon_{\psi_s} = (\psi_s)_{ref} - \hat{\psi}_s = \Delta \psi_s \quad (12)$$

$$\varepsilon_{\psi_r} = (\psi_r)_{ref} - \hat{\psi}_r = \Delta \psi_r \quad (13)$$

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

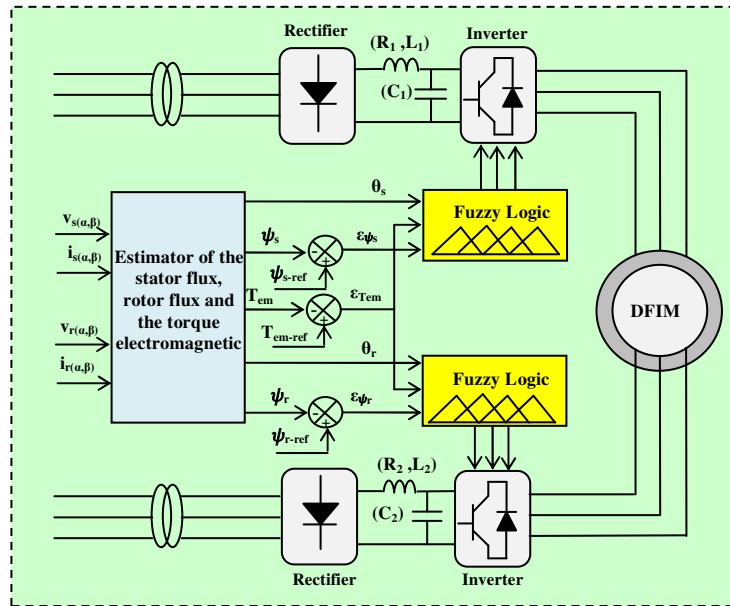


Figure 3. Synoptic schema of the fuzzy DTC applied to DFIM

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):

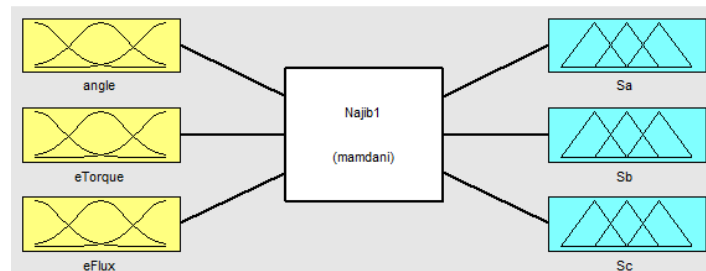


Figure 4. switching table by fuzzy logic

The universe of discourse of the flux position (stator flux or rotor flow) is divided into six fuzzy sets (θ_1 to θ_6). We choose the triangular membership function for all angles θ_i .

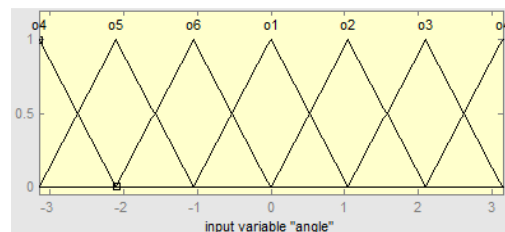


Figure 5. Membership function for flux position

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).

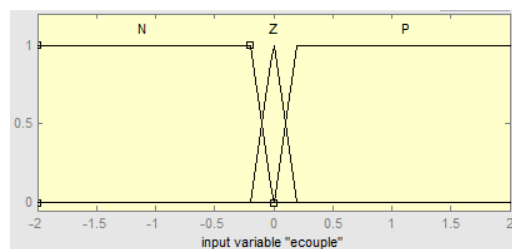


Figure 6. Membership function for error of the electromagnetic torque

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.

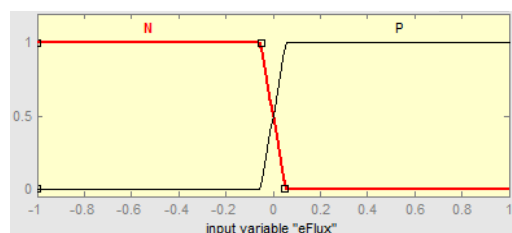


Figure 7. Membership function for flux error

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.

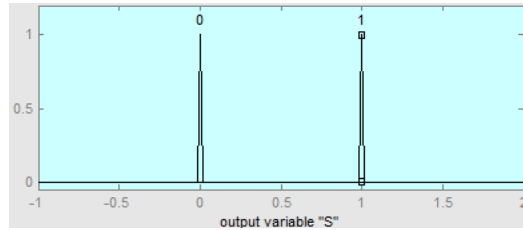


Figure 8. Membership functions for output variables

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

Table 1. Set of fuzzy rules

e_ψ	$e_{T_{em}}$	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
N	N	v_6	v_1	v_2	v_3	v_4	v_5
N	Z	v_7	v_0	v_7	v_0	v_7	v_0
N	P	v_2	v_3	v_4	v_5	v_6	v_1
P	N	v_5	v_6	v_1	v_2	v_3	v_4
P	Z	v_0	v_7	v_0	v_7	v_0	v_7
P	P	v_3	v_4	v_5	v_6	v_1	v_2

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.

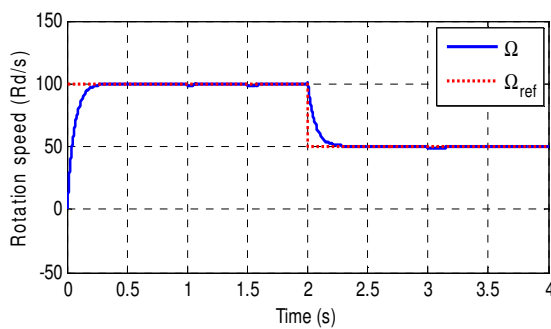


Figure 9. Rotation speed

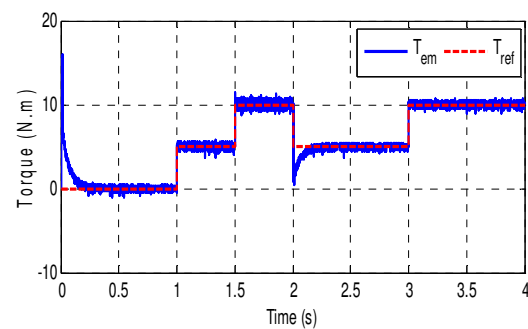


Figure 10. Electromagnetic torque

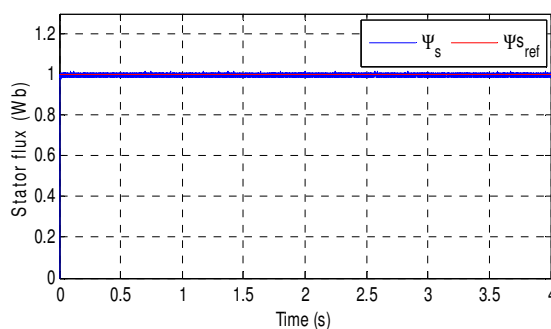


Figure 11. Stator flux

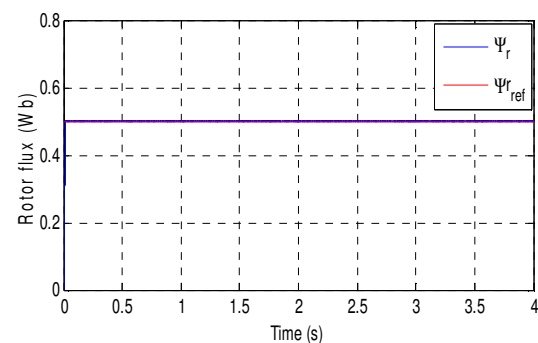
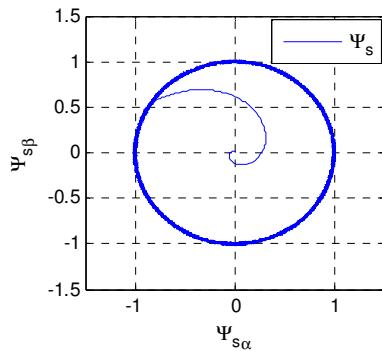
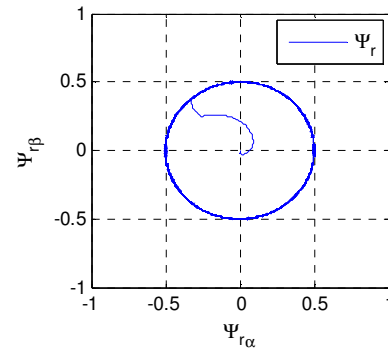


Figure 12. Rotor flux

**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 (α , β) 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
Rotator nominal voltage	V_{rn}	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 Ω
Rotor resistance	R_r	1.68 Ω
Total viscous frictions	f	0.0027 Kg.m ² /s
Total inertia	J	0.01 Kg.m ²

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