GU J Sci 31(2): 532-542 (2018)

Gazi University

Journal of Science

http://dergipark.gov.tr/gujs

High Performance Direct Torque Control of Doubly Fed Induction Motor using Fuzzy Logic

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Article Info

Received:07/12/2017
Accepted:25/02/2018

Keywords

Doubly Fed Induction Machine
Direct Torque Control
Fuzzy Logic Controller
Switching Table
Robustness

Abstract

Direct torque control (DTC) of Doubly Fed Induction Machine (DFIM) has large torque ripples and inconstant switching frequency, especially at low speed. This paper proposes an enhanced DTC method based on fuzzy logic technique. In order to improve the drawbacks of this conventional DTC and overcome the robustness problems against parametric variations of the DFIM, the switching tables and conventional PI regulator of speed are elaborated by the reasoning of fuzzy logic. A very detailed analysis of simulation results of the system in Matlab/Simulink environment is performed to the regarding to speed variation, reference tracking and robustness against system parameters variations. These results show the efficiency and robustness of this fuzzy logic controller for enhancing the performance of the DTC control of DFIM.

1. INTRODUCTION

The Doubly Fed Induction Machine (DFIM) is an induction machine with wound rotor whose stator and rotor windings are connected to two electric sources, it is very popular in industrial applications for its high electromechanical robustness, reliability, simplicity of construction and low cost [1,2]. This machine is essentially non-linear, due to the coupling between the flux and electromagnetic torque, hence the complexity of its control [3]. In the literature, several control techniques have been established to insure a wished regulation. These techniques are developed to return the successful and insensible system to the external disturbances and to the parametric variations. Among these control approaches we find the Field Oriented Control (FOC) by orientation of flux along a privileged axis which allows insuring a decoupling between the flux and the torque [4,5]. This decoupling allows obtaining a fast torque response, large speed control range and high efficiency for a wide load range in steady state. However, the variation of the electric and mechanical parameters degrades the performances of this control and can lead, in certain cases, to unstable functioning [6]. The direct torque control (DTC) comes to overcome the inherent inconveniences of the field oriented control, this one is based on the direct regulation of electromagnetic torque and the flux by direct determination of the control sequence to be applied to the voltage inverters [7,8], it is characterized by a good response time, good robustness and good stability. However, the torque and flux present important oscillations which can impair the functioning of the system [9]. Thus, it is well known that the speed control of the doubly fed induction machine with the PI correctors does not able to obtain very good performances when the speed set-point varies considerably (significant overshoot of the

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speed response) [10]. Indeed, during a large variation in the speed set-point, the corrector PI is in front of a large deviation, which causes a strong proportional action of the corrector which is translated by an overtaking of the motor speed [11]. In this context, the artificial intelligence techniques, especially the fuzzy logic, can be advisedly used for their qualities to solve some problems related to modeling errors as well as the lack of knowledge of the model of the system to be controlled. Like a conventional PI controller (proportional integral), a Fuzzy Logic Controller (FLC) [12], has the ability to improve the dynamic performance (tracking) and statics (rejection) of a curly control and it independently of the knowledge of model of the system to be controlled.

Our study concerns the variable speed motor operation of the DFIM, mainly in the study and the realization of robust commands by the DTC based on the fuzzy logic reasoning. The paper is organized as follows: Firstly, we present the three-phase mathematical model of DFIM and its transformation in the two-phase system. Secondly, we propose an intelligent control strategy based on fuzzy logic for the DTC control applied to doubly fed induction motor, the proposed control is constituted of an electromagnetic torque estimator, estimators of stator and rotor flux vectors and the fuzzy logic controllers. Finally, the performance and robustness of this control will be demonstrated by simulation results in the Matlab/Simulink environment.

2. MODELING OF THE DOUBLY FED INDUCTION MACHINE

For a better modeling of a doubly fed induction machine, it is necessary to use a specific, generic model and simple. In the stationary (a,b,c) reference frame, the relationships between the voltages, currents, and flux linkages of each phase of this machine, are time variant [13]. The time variant quantities can be made time invariant by transforming them into an appropriate rotating reference frame (d,q). Using park transforms, can be written from equations below [14].

The electrical and magnetic equations linked to stator of the DFIM in the reference (d,q) are expressed by:

- Stator voltages:

$$\begin{cases} v_{sd} = R_s.i_{sd} + \dfrac{d\psi_{sd}}{dt} - \omega_s.\psi_{sq} \\ v_{sq} = R_s.i_{sq} + \dfrac{d\psi_{sq}}{dt} + \omega_s.\psi_{sd} \end{cases} \tag{1}$$

- Stator currents:

$$\begin{cases} i_{sd} = \dfrac{1}{\sigma L_s}.\psi_{sd} - \dfrac{M}{\sigma L_s L_r}.\psi_{rd} \\ i_{sq} = \dfrac{1}{\sigma L_s}.\psi_{sq} - \dfrac{M}{\sigma L_s L_r}.\psi_{rq} \end{cases} \tag{2}$$

- Stator flux:

$$\begin{cases} \psi_{sd} = L_s.i_{sd} + M.i_{rd} \\ \psi_{sq} = L_s.i_{sq} + M.i_{rq} \end{cases} \tag{3}$$

The electrical and magnetic equations linked to rotor of the DFIM in the reference (d,q) are expressed by:

- Rotor voltages:

$$\begin{cases} v_{rd} = R_r.i_{rd} + \dfrac{d\psi_{rd}}{dt} - \omega_r.\psi_{rq} \\ v_{rq} = R_r.i_{rq} + \dfrac{d\psi_{rq}}{dt} + \omega_r.\psi_{rd} \end{cases} \tag{4}$$

- Rotor currents : $$\begin{cases} i_{rd} = \dfrac{1}{\sigma L_r}.\psi_{rd} - \dfrac{M}{\sigma L_s L_r}.\psi_{sd} \\ i_{rq} = \dfrac{1}{\sigma L_r}.\psi_{rq} - \dfrac{M}{\sigma L_s L_r}.\psi_{sq} \end{cases} \quad (5)$$

- Rotor flux: $$\begin{cases} \psi_{rd} = L_r.i_{rd} + M.i_{sd} \\ \psi_{rq} = L_r.i_{rq} + M.i_{sq} \end{cases} \quad (6)$$

The mechanical and electromechanical torque equations can be determined by the following relationship:

$$\begin{cases} T_{em} = T_r + J.\dfrac{d\Omega}{dt} + f.\Omega \\ T_{em} = p.(i_{sd}.\psi_{sq} - i_{sq.}\psi_{sd}) \end{cases} \quad (7)$$

With:

$V_{s(d,q)}, V_{r(d,q)}$	: Stator and rotor voltages in the reference of Park.
$I_{s(d,q)}, I_{r(d,q)}$	: Stator and rotor currents in the reference of Park.
$\psi_{s(d,q)}, \psi_{r(d,q)}$	: Stator and rotor flux in the reference of Park.
R_s, R_r	: Stator and rotor resistances.
L_s, L_r	: Stator and rotor inductances.
M	: Mutual inductance.
P	: Pole pair number.
σ	: Dispersion coefficient.
ω_s, ω_r	: Stator and rotor pulsations.
T_r, T_{em}	: Load and electromagnetic torque.
Ω	: Rotation speed.
J	: Inertia moment.
f	: Coefficient of friction.

3. FUZZY DIRECT TORQUE CONTROL

The direct torque control principle, presented by I. Takahashi is to regulate directly torque and flux of the machine by applying the various voltage vectors of the inverter, which determines its state [7,11]. The voltage vector choice is carried out by two switching tables.
The vector voltage of each two levels inverter can be expressed in the form below:

$$V = \sqrt{(2/3)}.U_0.(S_1 + S_2 e^{(j2\pi/3)} + S_3 e^{(j4\pi/3)}) \quad (8)$$

The various combinations of the three magnitudes (S_1,S_2,S_3) allow eight positions of the vector *V* represented by the figure below:

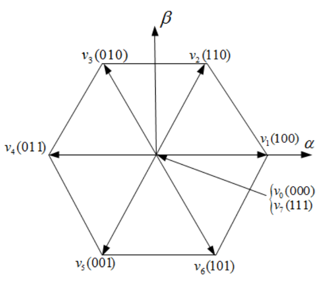

Figure 1. *Voltage vectors delivered by the inverter*

The Fuzzy Direct Torque Control (Fuzzy-DTC) gives better system performance, whose two switching tables are elaborated by the fuzzy logic approach.

The torque and flux error are calculated by comparing the reference value and the estimated value, as well as the position of flux vector are introduced to a fuzzy logic controller generating at its output the magnitudes (S_1, S_2, S_2) representing the switching state of the voltage inverter. The general structure of Fuzzy-DTC is illustrated by the following figure:

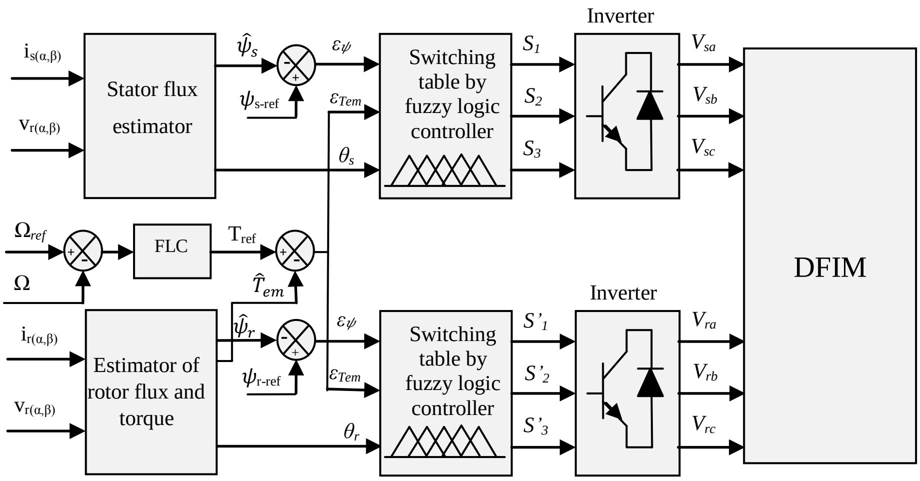

Figure 2. *Synoptic schema of the Fuzzy-DTC applied to DFIM*

3.1. Estimation of the flux and torque electromagnetic

The amplitude and position of the stator and rotor flux vectors are estimated from the currents and voltages measurements of the DFIM [12].
The stator and rotor flux vectors in the reference frame (α, β) are written:

$$\begin{cases} \hat{\psi}_{s\alpha} = \int_0^t (v_{s\alpha} - R_s.i_{s\alpha}).dt \\ \hat{\psi}_{s\beta} = \int_0^t (v_{s\beta} - R_s.i_{s\beta}).dt \\ \hat{\psi}_{r\alpha} = \int_0^t (v_{r\alpha} - R_r.i_{r\alpha}).dt \\ \hat{\psi}_{r\beta} = \int_0^t (v_{r\beta} - R_r.i_{r\beta}).dt \end{cases} \tag{9}$$

With: $\bar{\psi}_s = \hat{\psi}_{s\alpha} + j.\hat{\psi}_{s\beta}$ and $\bar{\psi}_r = \hat{\psi}_{r\alpha} + j.\hat{\psi}_{r\beta}$

The amplitude of the stator and rotor flux vectors can be expressed by:

$$\begin{cases} \hat{\psi}_s = \sqrt{\hat{\psi}_{s\alpha}^{\ 2} + \hat{\psi}_{s\beta}^{\ 2}} \\ \hat{\psi}_r = \sqrt{\hat{\psi}_{r\alpha}^{\ 2} + \hat{\psi}_{r\beta}^{\ 2}} \end{cases} \tag{10}$$

The position of the flux vectors is calculated as follows:

$$\begin{cases} \theta_s = arctg\left(\dfrac{\hat{\psi}_{s\beta}}{\hat{\psi}_{s\alpha}}\right) \\ \theta_r = arctg\left(\dfrac{\hat{\psi}_{r\beta}}{\hat{\psi}_{r\alpha}}\right) \end{cases} \tag{11}$$

The electromagnetic torque is estimated from the measured stator currents:

$$\hat{T}_{em} = p.(\hat{\psi}_{s\alpha}.i_{s\beta} - \hat{\psi}_{s\beta}.i_{s\alpha}) \tag{12}$$

3.2. Elaboration of the switching table

The switching states selection of the voltage inverters is carried out by two switching tables elaborated by two fuzzy logic controllers (FLC). In this system, torque error, flux error and flux angle are considered as inputs to each controller.

$$\varepsilon_{\psi s} = \psi_{s-ref} - \hat{\psi}_s = \Delta\psi_s \tag{13}$$

$$\varepsilon_{\psi r} = \psi_{r-ref} - \hat{\psi}_r = \Delta\psi_r \tag{14}$$

$$\varepsilon_{Tem} = T_{em-ref} - \hat{T}_{em} = \Delta T_{em} \tag{15}$$

These error functions are the differences between a magnitude calculated from the information supplied by the control and the equivalent magnitude determined from the estimates [15]. Each input is divided into a determined number of fuzzy sets. So, in order to have a better control using the minimum of rules, the following diagram illustrates Structure of the fuzzy controller for the two-level inverter.

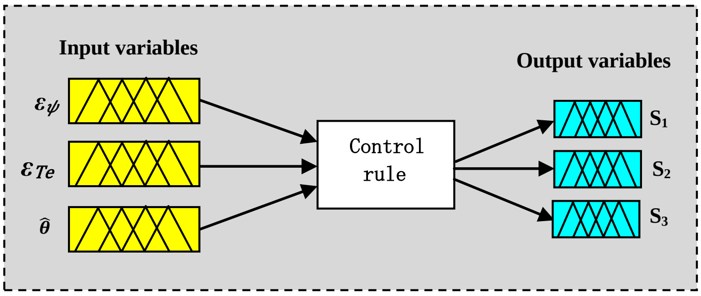

Figure 3. *Structure of the fuzzy logic controller for two-level inverter*

The first input variable is the flux error, his universe of discourse is divided into two fuzzy sets:

- Flux error is positive (P);
- Flux error is negative (N);

We choose the trapezoidal membership functions for the two fuzzy sets.

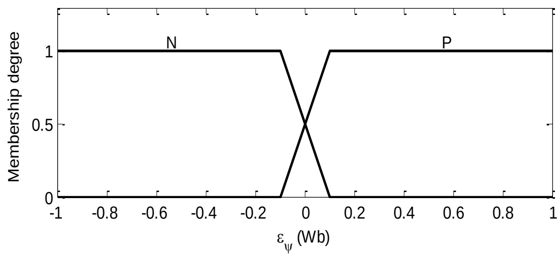

Figure 4. *Membership function for flux linkage error*

The second input is the electromagnetic torque error. His universe of discourse is divided into three fuzzy sets:

- Torque error is positive (P);
- Torque error is zero (Z);
- Torque error is negative (N).

We choose the trapezoidal membership functions for the two fuzzy sets (P) and (N) and the triangular membership function for fuzzy set (Z).

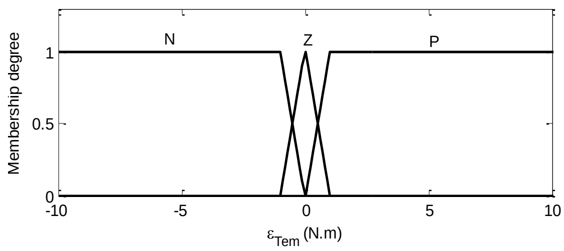

Figure 5. *Membership function for electromagnetic torque error*

The third input variable is the position of the flux (stator or rotor flux). The discourse universe of this variable is divided into six fuzzy sets (θ_1 to θ_6) whose membership functions are represented by figure 6. We choose the function of membership triangular for all angles θ_i.

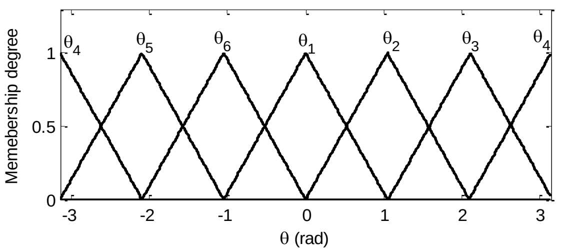

Figure 6. *Membership function for flux position*

The output variable is decomposed into three sub-outputs representing three switching magnitudes (S_1,S_2,S_3) of switches of the two-levels inverter, the universe of discourse of each output is divided into two fuzzy sets (zero and one).

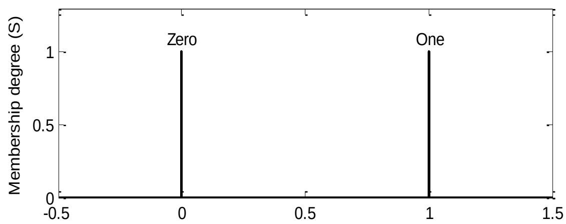

Figure 7. *Membership functions for output variables*

The fuzzy rules for determining the output variables of controller according to the input variables are grouped in following table:

Table 1. *Set of Fuzzy rules*

ε_ψ	ε_{Tem}	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
P	N	V_6(101)	V_1(100)	V_2(110)	V_3(010)	V_4(011)	V_5(001)
P	Z	V_7(111)	V_0(000)	V_7(111)	V_0(000)	V_7(111)	V_0(000)
P	P	V_2(110)	V_3(010)	V_4(011)	V_5 (001)	V_6(101)	V_1(100)
N	N	V_5(001)	V_6(101)	V_1(100)	V_2(110)	V_3(010)	V_4(011)
N	Z	V_0(000)	V_7(111)	V_0(000)	V_7(111)	V_0(000)	V_7(111)
N	P	V_3(010)	V_4(011)	V_5(001)	V_6(101)	V_1(100)	V_2(110)

The control algorithm then has 36 rules, the inference method used is Mamdani method based on the Max-Min decision, because it has the advantage of being easy to implement on the one hand and gives better results on the other hand.

The control rules are expressed as a function of the input and output variables as follows:
If (θ is X) and (ε_{Tem} is Y) and (ε_{ψ} is Z) then (V is V_i).
Where X, Y and Z are the fuzzy set of the input variables, V_i (S_1,S_2,S_3) the fuzzy set of the output variables.

3.3. Rotation speed regulation

In order to overcome the problems of conventional PI control of rotation speed, such as: response time, static error, rise time and overtaking. We propose a fuzzy logic controller (FLC) with as input the error and the derivation of speed error:

$$e(k) = \Omega_{ref}(k) - \Omega(k) \tag{16}$$

$$de(k) = e(k) - e(k-1) \tag{17}$$

The output of this speed controller is the reference torque value that the machine must develop. The following diagram illustrates the structure of fuzzy speed controller.

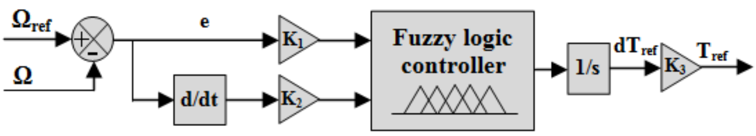

Figure 8. *Structure of fuzzy logic controller*

For the membership functions, the triangular and trapezoidal shapes were chosen for each variable as shown in the following figure:

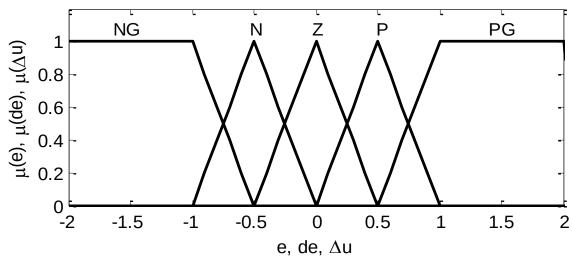

Figure 9. *Membership functions for the different of fuzzy controller variables*

The Max-Min inference method of Mamdani is adopted. From the study of system behavior, we can establish the control rules, which connect the output with the inputs. Each of the two language inputs of the fuzzy controller has five fuzzy sets, resulting in a set of 25 rules. These can be represented by the following inference matrix:

Table 2. *Inference matrix*

de \ e	NG	N	EZ	P	PB
NB	NB	NB	N	N	Z
N	NB	N	Z	Z	P
EZ	N	N	Z	P	P
P	N	Z	P	P	PB
PB	Z	P	P	PB	PB

With: PB positive big, P positive, EZ zero, N negative and NB negative big are fuzzy sets of FLC.

4. SIMULATION RESULTS

To verify the performances, robustness and asymptotic stability of the Fuzzy-DTC control and balance system, we have implemented and realized several numerical simulation series for the DFIM-Converter system in the Matlab/Simulink environment, with variable functioning conditions.

4.1. Variable speed operation with load torque application

The following figures show the behavior of electrical, magnetic and mechanical magnitudes of the machine during a complete cycle with load torque application.

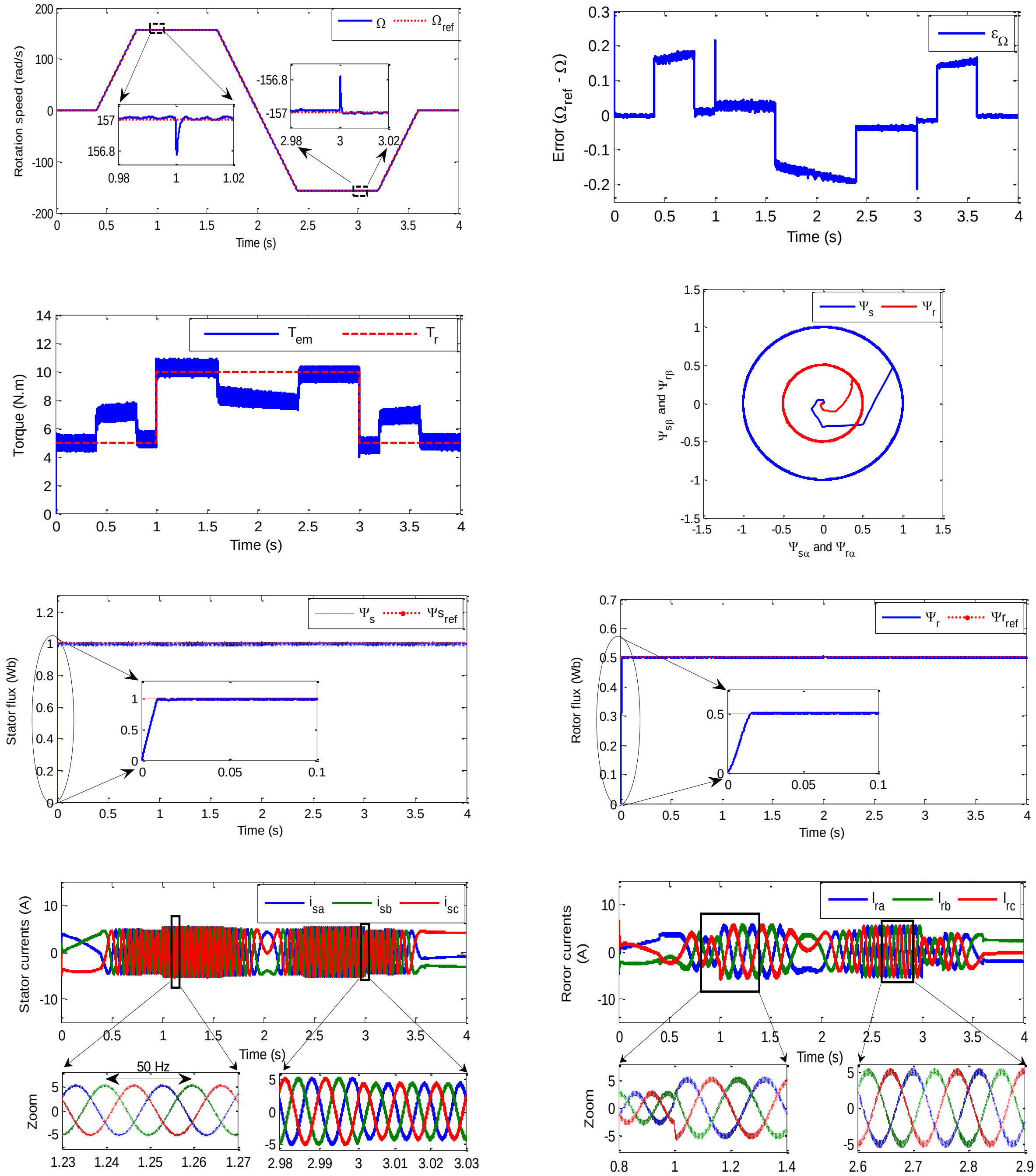

Figure 10. *System response at trapezoidal speed with load torque application*

The simulation results show a good behavior of the DFIM despite the load torque variation, we observe that the rotation speed follows perfectly and rapidly its reference value with a static error converges to zero. The electromagnetic torque follows its reference value, it stabilizes at that of the load torque because the speed regulator reacts instantaneously to the reference torque in order to produce, as the case may be, an acceleration or deceleration of the rotational speed. The stator and rotor flux remain at their nominal value without the exceeding with a fast response time. The stator and rotor currents are sinusoidal and exhibit variations depending on the changes in the load torque, the speed and in particular during the reversal of rotation.

4.2. Robustness test

In order to test the robustness of the control, we will study the influence of the parametric variations (stator and rotor resistances, stator and rotor inductances and inertia coefficient) of the doubly fed induction motor.

4.2.1. Variation in the stator and rotor resistances

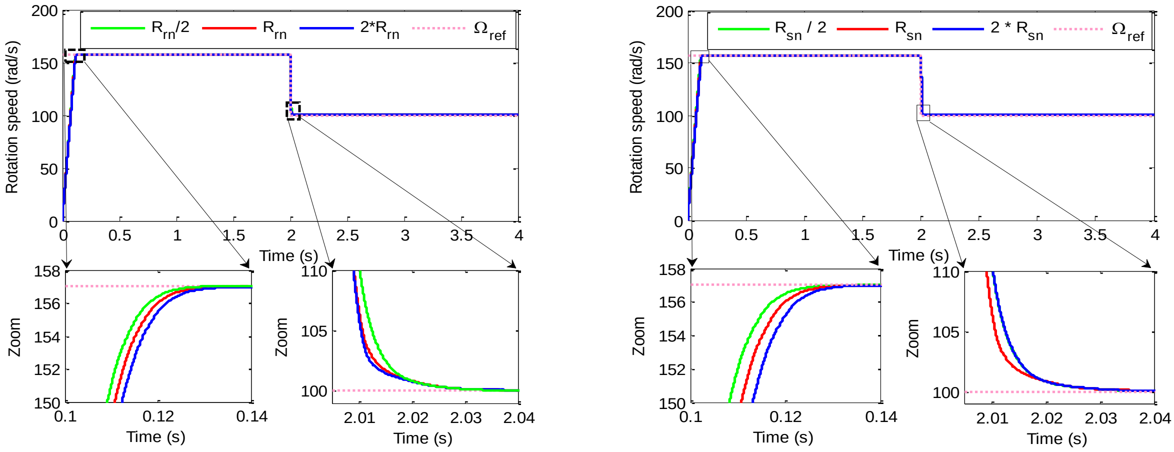

Figure 11. *Robustness test for a variation in the rotor and stator resistances*

4.2.2. Variation in the stator and rotor inductances

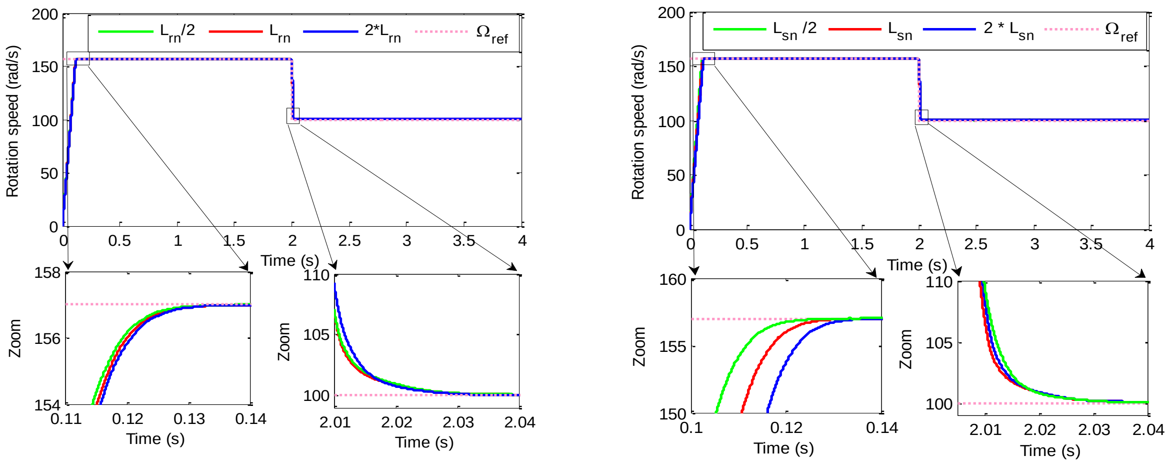

Figure 12. *Robustness test for a variation in the rotor and stator inductances*

4.2.3. Variation in the inertia coefficient

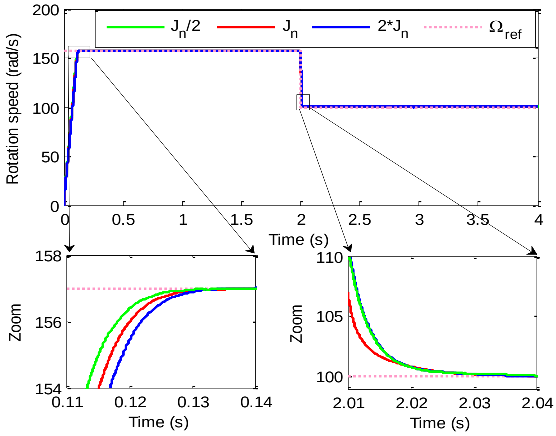

Figure 13. *Robustness test for a variation in the inertia coefficient*

The results obtained for the robustness test of the Fuzzy-DTC control show that the parametric variations of the DFIM has no influence on the behavior of the motor, a variation in the resistance or inductance of its nominal value doesn't affect the response time which remains constant, but the rise time is varied.

5. CONCLUSION

The aim of this work was to develop, improve and study the robustness of a new strategy of direct torque control based on the reasoning of fuzzy logic for a doubly fed induction machine functioning in motor mode directly connected to two voltage converters. The results obtained confirm the effectiveness of Fuzzy-DTC strategy used for controlling the system based on the DFIM and attests the desired performances and robustness.

Appendix:

Table 3. *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_{rn}	130 V
Pair pole number	P	2
Stator self inductance	L_s	0.295 H
Rotor self inductance	L_r	0.104 H
Mutual inductance	M	0.165 H
Stator resistance	R_s	1.75 Ω
Rotor resistance	R_r	1.68 Ω
Coefficient of frictions	f	0.0027 $Kg.m^2/s$
Inertia moment	J	0.01 $Kg.m^2$

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors

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