Article citation info:
Herizi A, Rouabhi R, Zemmit A. Speed control of doubly fed induction motor using backstepping control with interval type-2 fuzzy controller. Diagnostyka. 2023;24(3):2023301. https://doi.org/10.29354/diag/166460.

DIAGNOSTYKA, 2023, Vol. 24, No. 3

e-ISSN 2449-5220
DOI: 10.29354/diag/166460

SPEED CONTROL OF DOUBLY FED INDUCTION MOTOR USING BACKSTEPPING CONTROL WITH INTERVAL TYPE-2 FUZZY CONTROLLER

Abdelghafour HERIZI [1, 2,*], Riyadh ROUABHI [1, 2], Abderrahim ZEMMIT [1]

[1] Electrical Engineering Department, Faculty of Technology, University Mohamed Boudiaf of M'sila, Algeria
[2] LGE Research Laboratory of M'sila, Algeria
[*] Corresponding author, e-mail: abdelghafour.herizi@univ-msila.dz

Abstract

The control of the doubly-fed induction motor is a complex operation because of this motor characterised by a non-linear multivariable dynamics, having settings that change over time and a significant link between the mechanical component and magnetic behavior (flux) (speed and couple). This article then proposes a new strategy of a robust control of this motor, which is decoupled due to the stator flux's direction. The proposed control is integrated with the backstepping control which based on Lyapunov theory; this approach consists in constructively designing a control law of nonlinear systems by considering some state variables as being virtual commands, and the important branch of artificial intelligence type-2 fuzzy logic. The hybrid control backstepping-fuzzy logic consists in replacing the regulators applied to the backstepping control by regulators based on type-2 fuzzy logic. This control will be evaluated by numerous simulations where there is a parametric and non-parametric variation.

Keywords: doubly-fed induction motor, type-2 fuzzy logic, backstepping control, hybrid control, robust.

1. INTRODUCTION

Asynchronous machines are the most used in industrial sectors due to low cost, reduced mass, robustness, simple construction and minimum maintenance, although these require internal structures and more complex control strategies [1], [2].

A three-phase asynchronous machine wound rotor supplied by two voltage sources, one at the stator and the other at the rotor, has been the subject of numerous investigations. This device is known as a doubly fed induction motor "DFIM" [3], have recently been published. The latter is a great alternative for high power and variable speed drives, thanks to the development of power electronics equipment and the appearance of new control approaches. The benefit of such devices is that they operate at a relatively low speed. Another advantage of employing these machines is the ability to provide multiple control techniques by combining DFIMs with static converters. The variable frequency rotor circuit power supply makes it possible to deliver a fixed frequency to the stator even in the event of a speed variation. This operation presents the doubly fed induction motor as a serious alternative to conventional synchronous machines in many electric drive systems [4].

Despite its many advantages, the doubly fed induction motor control remains one of the most difficult compared to that of a direct current machine, because its mathematical model is nonlinear and heavily coupled, the polar opposite of its structural simplicity. The vector controls enable dynamic performance equivalent to that of the direct current machine in order to achieve decoupled control of the induction machine through the application of appropriate marks. However, experience has highlighted some weaknesses of this method in the face of disturbances due to uncertainties in the parameters, whether they are measured, such as the speed of the motors, or that they vary during operation, such as the resistances of the rotor and the stator [5], [6].

Such drawbacks have pushed researchers towards the development of nonlinear control techniques; we can non-exhaustively distinguish the sliding mode control which boomed at the end of the seventies when "Utikin" introduced the theory of sliding modes [7], [8]. Other researchers have been able to design other comparable controls on the performance side, in this case the backstepping control. M. Krstic and P. V. Kokotovic [9], [10], proposed approaches on types of parametric nonlinear triangular systems that used changes in dynamic variables and a Lyapunov function. In general, the principle is to use some state variables

Received 2023-02-22; Accepted 2023-05-24; Available online 2023-06-28

as virtual controls and develop intermediary control laws for them to construct the nonlinear system's control rule [11], [12].

On the other hand, over the past 20 years, there has been a substantial advancement. In fact, a brand-new discipline called artificial intelligence has emerged as a result of the development of unique approaches including fuzzy logic, neural networks, genetic algorithms, and others. The limits of conventional techniques can be overcome and system control can be improved thanks to artificial intelligence techniques [13].

One of the most important branches of artificial intelligence is fuzzy logic. The theoretical bases of this logic were established in 1965 by Professor Lotfi Zadeh at Berekley University in California, who introduced the notion of the fuzzy set [14], [15]. This makes it possible to obtain an often very effective adjustment law without having to carry out in-depth modeling. The fuzzy logic regulator, unlike a standard or state feedback regulator, does not deal with a well-defined mathematical relationship, instead relying on inferences based on linguistic variables. As a result, the experiences of the operators of a technical process can be taken into account. One of the most often utilized methods for strengthening control, resilience against parametric and nonparametric variation is fuzzy logic [16], [17].

In light of what has been said, the last few years have seen the emergence of a certain trend towards combining different control techniques with fuzzy logic to achieve higher performance controls taking advantage of the advantages offered by each. The main objective of this article is to combine type-2 fuzzy logic with backstepping control. This association will be exploited to improve the dynamic responses of the DFIM.

2. DOUBLY-FED INDUCTION MOTOR MODEL

A fifth-order DFIM that incorporates both the electrical and mechanical dynamic is provided as [13], [17] based on the suppositions of a linear magnetic circuit and equal mutual inductance.

$$\begin{cases}\dot{\varphi_{sd}} = -\frac{1}{T_s}\varphi_{sd} + \omega_s\varphi_{sq} + \frac{M}{T_s}I_{rd} + V_{sd}\\ \dot{\varphi_{sq}} = -\omega_s\varphi_{sd} - \frac{1}{T_s}\varphi_{sq} + \frac{M}{T_s}I_{rq} + V_{sq}\\ \dot{I_{rd}} = \alpha\varphi_{sd} - \beta\omega\varphi_{sq} - \delta I_{rd} + \gamma I_{rq} - \frac{MV_{sd}}{\sigma L_s L_r} + \frac{V_{rd}}{\sigma L_r}\\ \dot{I_{rq}} = \beta\omega\varphi_{sd} + \alpha\varphi_{sq} - \gamma I_{rd} - \delta I_{rq} - \frac{MV_{sq}}{\sigma L_s L_r} + \frac{V_{rq}}{\sigma L_r}\\ \dot{\Omega} = -\frac{1}{J}\left(P\frac{M}{L_s}\varphi_{sd}I_{rq} + f\Omega + C_r\right)\end{cases} \tag{1}$$

With:

$\sigma = 1 - \frac{M^2}{L_r L_s}$; $T_r = \frac{L_r}{R_r}$; $T_s = \frac{L_s}{R_s}$; $\alpha = \frac{M}{\sigma L_r L_s T_s}$; $\beta = \frac{M}{\sigma L_r L_s}$; $\delta = \frac{1}{\sigma}\left(\frac{1}{T_r} + \frac{M^2}{L_s T_s L_r}\right)$; $\gamma = \omega_s - \omega$

The electro-magnetic equation is given in the following manner:

$$C_{em} = P\frac{M}{L_s}\left(\varphi_{sq}I_{rd} - \varphi_{sd}I_{rq}\right) \tag{2}$$

Where: L_s and L_r: cyclic inductors, M: maximum mutual inductance, f: coefficient of friction, J: moment of inertia, P: number of pole pairs, Ω: rotor speed, C_r: resistive torque. Rotor and stator are indicated by the subscripts r and s, respectively.

2.1. Field oriented transformation

The principle of stator flux orientation in direct park transformation is illustrated in Fig. 1 [3], [13], [17]. The state vector representations for the fixed stator coordinate (a, b) and the frame (d, q), which rotates with the rotor, are transformed in this control technique to produce an approximately linear and decoupled control system.

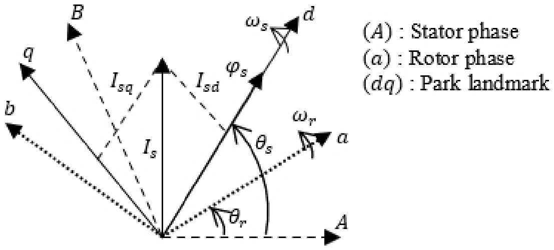

Fig. 1. Direction of stator flux on axis d

By selecting a (d, q) frame of reference associated, given the revolving stator area and the capability of using the d axis to align the stator flux vector, this consequence in: $\varphi_{sd} = \varphi_s$ and $\varphi_{sq} = 0$.

Assuming that the electric community is steady, the resulting value is the φ_s constant. Furthermore, the stator resistance can be disregarded. Based on these factors, we reach the following results: $V_{sd} = 0$, $V_{sq} = V_s$ and $V_{sq} = V_s/\omega_s$.

The adaptation of the above equations to the simplifying hypotheses results in:

$$\begin{cases}I_{sd} = \frac{\varphi_s}{L_s} - \frac{M}{L_s}I_{rd}\\ I_{sq} = -\frac{M}{L_s}I_{rq}\end{cases} \tag{3}$$

$$\begin{cases}\varphi_{rd} = \left(L_r - \frac{M^2}{L_s}\right)I_{rd} + \frac{V_s M}{\omega_s L_s}\\ \varphi_{rq} = \left(L_r - \frac{M^2}{L_s}\right)I_{rd}\end{cases} \tag{4}$$

The Backstepping approach, which we will apply to the control of the DFIM, is based on the principle of the orientation of the stator flux. The model of the machine, equation 1, in the reference (d, q) is given by:

$$\begin{cases}\dot{\varphi}_{sd} = \frac{M}{T_s}I_{rd} - \frac{1}{T_s}\varphi_{sd} + V_{sd}\\ \dot{\varphi}_{sq} = \frac{M}{T_s}I_{rq} - \omega_s\varphi_{sd} + V_{sq}\\ \dot{I}_{rd} = -\delta I_{rd} + \gamma I_{rq} + \alpha\varphi_{sd} - \frac{MV_{sd}}{\sigma L_s L_r} + \frac{V_{rd}}{\sigma L_r}\\ \dot{I}_{rd} = -\gamma I_{rd} - \delta I_{rq} + \beta\omega\varphi_{sd} - \frac{MV_{sq}}{\sigma L_s L_r} + \frac{V_{rq}}{\sigma L_r}\\ \dot{\Omega} = -\frac{1}{J}\left(P\frac{M}{L_s}\varphi_{sd}I_{rq} + f\Omega + C_r\right)\end{cases} \tag{5}$$

3. BACKSTEPPING DESIGN

The backstepping control is a nonlinear synthesis technique while it’s far tough to use the direct lyapunov technique. It is an issue to begin with deciding on a lyapunov function for the primary subsystem and growing it because the numerous successive subsystems have stability, should ultimately seem as having a global Lyapunov function that stabilizes the overall system [13], [17].

The first step is composed in figuring out the errors z_1 and z_2 which respectively constitute the mistake among the actual speed Ω and the reference speed Ω_{ref} in addition to the rotor flux modulus φ_{sd} and the reference one φ_{sd}^{ref}.

$$\begin{aligned} z_1 &= \Omega_{ref} - \Omega \\ z_2 &= \varphi_{sd}^{ref} - \varphi_{sd} \end{aligned} \tag{6}$$

The derivative of the error is given by:

$$\begin{aligned} \dot{z}_1 &= \dot{\Omega}_{ref} + \frac{1}{J}\left(P\frac{M}{L_s}\varphi_{sd}I_{rq} + f\Omega + C_r\right) \\ \dot{z}_2 &= \dot{\varphi}_{sd}^{ref} - \left(\frac{M}{T_s}I_{rd} - \frac{1}{T_s}\varphi_{sd} + V_{sd}\right) \end{aligned} \tag{7}$$

The primary function of Lyapunov is defined as:

$$v_1 = \frac{1}{2}(z_1^2 + z_2^2) \tag{8}$$

Then, the derivative of (8) is calculated as:

$$\dot{v}_1 = z_1\left(\dot{\Omega}_{ref} + \frac{1}{J}\left(P\frac{M}{L_s}\varphi_{sd}I_{rq} + f\Omega + C_r\right)\right) + z_2\left(\dot{\varphi}_{sd}^{ref} - \left(\frac{M}{T_s}I_{rd} - \frac{1}{T_s}\varphi_{sd} + V_{sd}\right)\right) \tag{9}$$

The stabilizing functions are chosen as follows:

$$\begin{cases} I_{rq}^{ref} = -\frac{JL_s}{pM\varphi_{sd}}\left(k_1 z_1 + \dot{\Omega}_{ref} + \frac{f}{J}\Omega + \frac{C_r}{J}\right) \\ I_{rd}^{ref} = \frac{T_s}{M}\left(k_2 z_2 + \dot{\varphi}_{sd}^{ref} - V_{sd} + \frac{1}{T_s}\varphi_{sd}\right) \end{cases} \tag{10}$$

Where: k_1 and k_2 are positive constants. After that, equation (7) can be expressed as follows:

$$\begin{aligned} \dot{z}_1 &= -k_1 z_1 \\ \dot{z}_2 &= -k_2 z_2 \end{aligned} \tag{11}$$

And $\dot{v}_1$, equation (9), given by:

$$\dot{v}_1 = -k_1 z_1^2 - k_2 z_2^2 < 0 \tag{12}$$

The second step, two new errors of the current components provided by:

$$\begin{aligned} z_3 &= I_{rq}^{ref} - I_{rq} \\ z_4 &= I_{rd}^{ref} - I_{rd} \end{aligned} \tag{13}$$

Where: $I_{rq}^{ref} = -\frac{JL_s}{pM\varphi_{sd}}\left(k_1 z_1 + \dot{\Omega}_{ref} + \frac{f}{J}\Omega + \frac{C_r}{J}\right)$ and $I_{rd}^{ref} = \frac{T_s}{M}\left(k_2 z_2 + \dot{\varphi}_{sd}^{ref} - V_{sd} + \frac{1}{T_s}\varphi_{sd}\right)$

The derivative of equation (13) gives us:

$$\begin{aligned} \dot{z}_3 &= \dot{I}_{rq}^{ref} - \dot{I}_{rq} = \dot{I}_{rq}^{ref} - \left(\eta_1 + \frac{1}{\sigma L_r}V_{rq}\right) \\ \dot{z}_4 &= \dot{I}_{rd}^{ref} - \dot{I}_{rd} = \dot{I}_{rd}^{ref} - \left(\eta_2 + \frac{1}{\sigma L_r}V_{rd}\right) \end{aligned} \tag{14}$$

Or:

$$\eta_1 = -\gamma I_{rd} - \delta I_{rq} + \beta\omega\varphi_{sd} - \frac{M}{\sigma L_s L_r}V_{sq}$$

$$\eta_2 = -\delta I_{rd} + \gamma I_{rq} + \alpha\varphi_{sd} - \frac{M}{\sigma L_s L_r}V_{sd}$$

In the Step 3, the equations obtained in step 1 and step 2 of the backstepping method is used to define the control laws by the following expression:

$$v_2 = \frac{1}{2}(z_1^2 + z_2^2 + z_3^2 + z_4^2) \tag{15}$$

Thus the derived from the final function of Lyapunov is:

$$\dot{v}_2 = z_1\dot{z}_1 + z_2\dot{z}_2 + z_3\dot{z}_3 + z_4\dot{z}_4 \tag{16}$$

This equation can be rewritten by:

$$\dot{v}_2 = z_1\dot{z}_1 + z_2\dot{z}_2 + z_3\left(k_3 z_3 + \dot{I}_{rq}^{ref} - \eta_1 - \frac{1}{\sigma L_r}V_{rq}\right) + z_4\left(k_4 z_4 + \dot{I}_{rd}^{ref} - \eta_2 - \frac{1}{\sigma L_r}V_{rd}\right) \tag{17}$$

We choose the command as follows:

$$\begin{aligned} V_{rq}^{ref} &= \sigma L_r\left(k_3 z_3 + \dot{I}_{rq}^{ref} - \eta_1\right) \\ V_{rd}^{ref} &= \sigma L_r\left(k_4 z_4 + \dot{I}_{rd}^{ref} - \eta_2\right) \end{aligned} \tag{18}$$

The choice of $k_3 > 0$ and $k_4 > 0$ can be made such that $\dot{v}_2 < 0$. Equation (14) can be expressed as:

$$\begin{aligned} \dot{z}_3 &= -k_3 z_3 \\ \dot{z}_4 &= -k_4 z_4 \end{aligned} \tag{19}$$

The matrix form of the errors is given by:

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \\ \dot{z}_4 \end{bmatrix} = \begin{bmatrix} -k_1 & 0 & \frac{PM\varphi_{sd}}{JL_s} & 0 \\ 0 & -k_2 & 0 & \frac{M}{T_s} \\ 0 & 0 & -k_3 & 0 \\ 0 & 0 & 0 & -k_4 \end{bmatrix} \cdot \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} \tag{20}$$

The stability is obtained if only good choices of the gains k_i.

4. HYBRID CONTROL BACKSTEPPING-IT2FLC

4.1. Interval type-2 fuzzy logic system

The type-2 membership function $\mu_{\tilde{A}}(x)$ that describes a T2FS in the universal set X is indicated as $\tilde{A}$. $\tilde{A}$ is also known as a secondary membership function (MF) or secondary set, which is a type-1 set in [0, 1] [18 - 21].

$$\tilde{A} = \int_{x\in X}\mu_{\tilde{A}}(x)/(x) = \int_{x\in X}\left[\int_{u\in J_x} f_x(u)/(u)\right]/(x) \quad J_x \subseteq [0,1] \tag{21}$$

Where:

$f_x(u) = 1, \forall u \in J_x \subseteq [0,1], \forall x \in X.$

The secondary MFs are interval sets that qualify as interval type-2 MFs for $\mu_{\tilde{A}}(x)$ [22]. Consequently, T2FS $\tilde{A}$ can be written as follows:

$$\tilde{A} = \int_{x\in X}\mu_{\tilde{A}}(x)/(x) = \int_{x\in X}\left[\int_{u\in J_x} 1/(u)\right]/(x) \quad J_x \subseteq [0,1] \tag{22}$$

The defuzzifier block in a T1FLC is replaced by the output processing block in a T2FLS, which comprises of type-reduction and defuzzification. The main structural distinction between a T2 FLS and a T1 FLS is this [22].

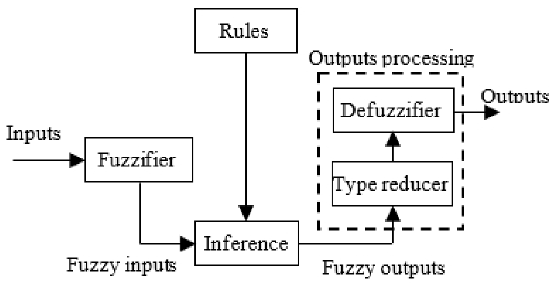

Fig. 2. Structure of T2FLS [18]

We only consider singleton input fuzzification throughout this paper. Similar to T1FLS, the firing strength in (23) can be obtained by following firing strength F inference process:

$$F^i = \coprod_{x\in X}\left[\prod_{k=1}^{n}\mu_{\tilde{F}_k^i}(x_k)\right] \quad (23)$$

Where:

$\prod$ the meet operation and $\coprod$ the join operation are both present [22].

The upper MF and lower MF are subsets with the highest and lowest membership grades, respectively, for the Gaussian IT2FS depicted in Fig. 3. The result of meet operations using the maximum value are merged by the join operation in (23). The operation can result in an interval type-1 set [23] that looks like this:

$$F^i \equiv \left[\underline{f}^i, \bar{f}^i\right] \quad (24)$$

With:

$\underline{f}^i$ and $\bar{f}^i$ are given as:

$$\underline{f}^i = \underline{\mu}_{F_1^i}(x_1) \times \dots \times \underline{\mu}_{F_p^i}(x_n)$$
$$\bar{f}^i = \bar{\mu}_{F_1^i}(x_1) \times \dots \times \bar{\mu}_{F_n^i}(x_n) \quad (25)$$

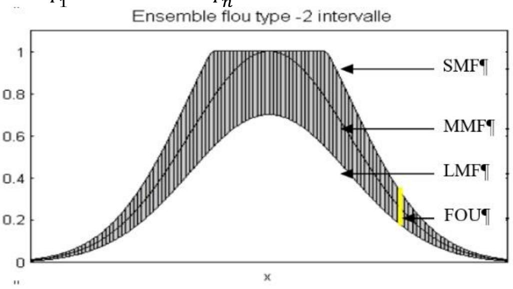

Fig. 3. Fuzzy type-2 Gaussian set for intervals

Type reduction bay recommended According to Karink and Mendel's use of the center of set approach in (24): [22 - 24]

$$Y_{cos}(x) = [y_l(x), y_r(x)]$$
$$= \int_{y^1\in[y_l^1,y_r^1]} \cdots \int_{y^M\in[y_l^M,y_r^M]} \int_{f^1\in[\underline{f}^1,\bar{f}^1]} \cdots \int_{f^M\in[\underline{f}^M,\bar{f}^M]} \frac{1}{\frac{\sum_{i=1}^{M} f^i y^i}{\sum_{i=1}^{M} f^i}} \quad (26)$$

As a result, [24] can be used to express the left-most point y_l and the right-most point y_r.

$$\begin{cases} y_l(x) = \frac{\sum_{i=1}^{M} f_l^i y_l^i}{\sum_{i=1}^{M} f_l^i} \\ y_r(x) = \frac{\sum_{i=1}^{M} f_r^i y_r^i}{\sum_{i=1}^{M} f_r^i} \end{cases} \quad (27)$$

The defuzzified crisp output of an interval type-2 FLS is the average of:

$$Y(x) = \frac{y_l(x) + y_r(x)}{2} \quad (28)$$

4.2. A DFIM's Backstepping-interval type 2 FLC

The design of a new nonlinear drive for a doubly fed induction motor is described in this section. To increase the robustness of the suggested control, a type-2 fuzzy controller and the Backstepping control method are used in its construction. We demonstrate that the trajectory tracking dynamics are asymptotically stable using Lyapunov's stability theory. We use the control by stator flux orientation, which has the benefit of separating the flux and current, in order to simplify the control. In order to replace the gains of the rules of the backstepping command, by an input (the error between the measured value and their reference) and one output, the gain k_i, this method uses a type-2 fuzzy controller.

4.2.1. A DFIM type-2 fuzzy controller is being developed

In what follows, the regulators are replaced by a fuzzy regulator to obtain a robust and efficient control. A equivalent control $\left(u_{I_{rq}}\right)$ that depicts the state trajectory along the difference between the measured value and the reference value, regulator based on fuzzy logic (u_r) are contained in this interval type-2 FLC backstepping control (IT2FBC), figure 3, proposed by the following equation:

$$u_{IT2FBC} = u_{I_{rq}} + u_r \quad (29)$$

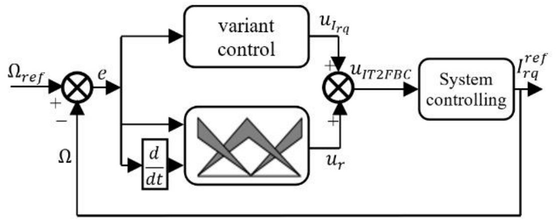

Fig. 4. Schematic of hybrid control backstepping-type-2 FLC

Where:

u_r is the fuzzy control (interval type-2 FLC), is a constant that has been chosen to satisfy the robustness criterion; The following section offers the mathematical justification for this control.

$$u_r = k_f u_f; \quad u_f = IT2FLC(e) \quad (30)$$

Where:

The output variable's normalization factor is k_f, and the IT2FLC's output, u_f, is produced by normalizing e.

Given the following equation, the hybrid control backstepping-type 2 fuzzy controller (IT2FBC) created in this work:

$$I_{rq}^{ref} = u_{I_{rq}} + u_r \Rightarrow$$
$$u_{I_{rq}} = -\frac{JL_s}{pM\varphi_{sd}}\left(\dot{\Omega}_{ref} + \frac{f}{J}\Omega + \frac{C_r}{J}\right)$$
$$u_r = -\frac{JL_s}{pM\varphi_{sd}}\left(k_f u_f\right) \quad (31)$$

4.2.2. Proposed interval type-2 fuzzy logic control

The current error is the variation in currents between the reference value and the measured value, serves as the fuzzy system's first input while the error derivative of the latter serves as its second input. Figures 5 and 6 display the input error (e) and derivative error $(\dot{e})$ fuzzy type-2 membership functions.

Five language labels are used to identify the entries: NB (Negative Big), N (Negative), ZE (Zero), P (Positive), and PB (Positive Big). All labels' MFs are set to be Gaussian for the inputs.

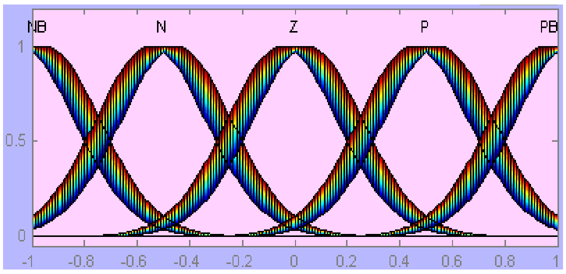

Fig. 5. Interval type-2 membership function for input e

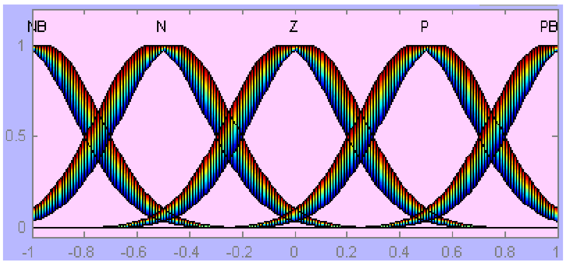

Fig. 6. Interval type-2 membership function for input $\dot{e}$

If we have five values for the error (e) and five values for the derivative of the error $(\dot{e})$, we will require 25 rules to account for all potential inputs. In a table, these are typically written as follows:

Table 1. For type-2 FLCs, fuzzy rules.

Control		$e(t)$				
		NB	N	Z	P	PB
$\dot{e}(t)$	NB	NB	NB	N	N	Z
	N	NB	N	N	Z	P
	Z	N	N	Z	P	P
	P	N	Z	P	P	PB
	PB	Z	P	P	PB	PB

Figure 7 displays the output (u_f) discontinuous control's membership functions.

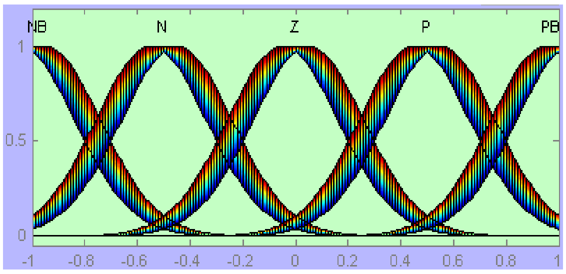

Fig. 7. Membership function for output

Figure 8 provides the diagram of the type-2 fuzzy backstepping control (IT2FBC). Obtaining the currents of I_{rq}^{ref} and I_{rd}^{ref}, which constitute the dummy control, is the control's first step. The new errors z_3 and z_4 cause the error between these references and the true quantities of the currents. Finally, to ensure the machine's stability, we tend to alter the control laws V_{rq}^{ref} and V_{rd}^{ref} from equation (18).

5. SIMULATION RESULTS

This step's goal is to operate the hybrid type-2 fuzzy backstepping control to regulate the doubly fed induction motor with stator flux orientation. Different tests will be applied to show the performance of this control, namely, the variation of the torque, speed and the parametric variation rotor resistance. Parameters of the DFIM used is in [3].

5.1. Machine operation during torque variation

Figure (9) illustrates the behavior of the DFIM under load after an empty start. At the instant $t = 1.5s$, we apply a load of value $C_r = 15N.m$. Considering the results obtained, we notice that the torque responds quickly to compensate the load with a negligible influence on the speed. The flux always remains constant, which explains the decoupling between the flux and the torque.

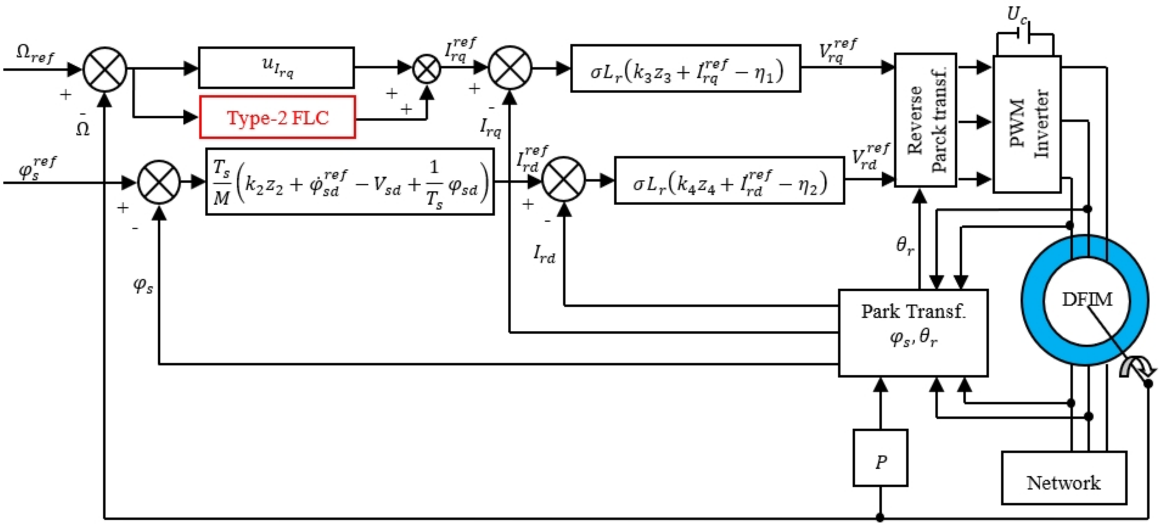

Fig. 8. System block diagram of the IT2FBC of the DFIM

5.2. Machine operation when varying the speed

Figure (10) represents the evolution of the characteristics of the DFIM during the variation of the direction of rotation. At the instant $t = 1.5s$, the direction of rotation of the machine is reversed by (-157rad/s) and at the instant $t = 2.5s$ the machine is spinning at a low speed of 50 rad/s.

5.3. Machine operation during R_r variation

In a figure (11), the simulation results are compiled. In this test, the rotor resistance was increased by +100% of its nominal value between times $t = 1.5s$ and $t = 2.5s$.

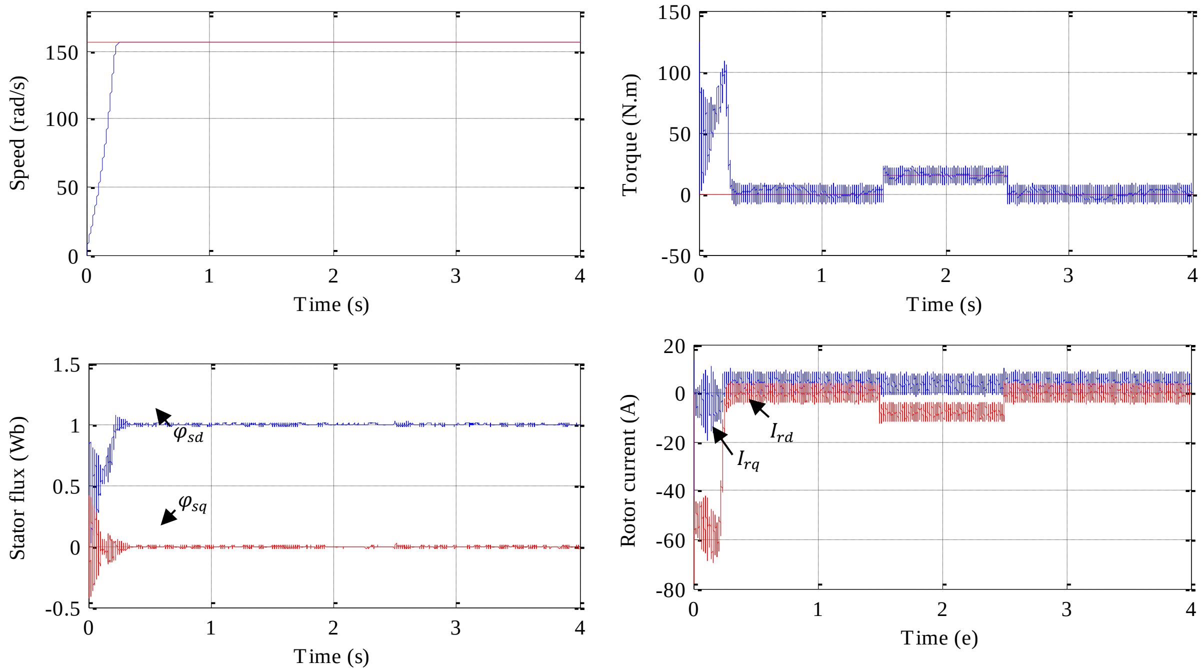

Fig. 9. Simulation results of IT2FBC of the DFIM with during torque variation

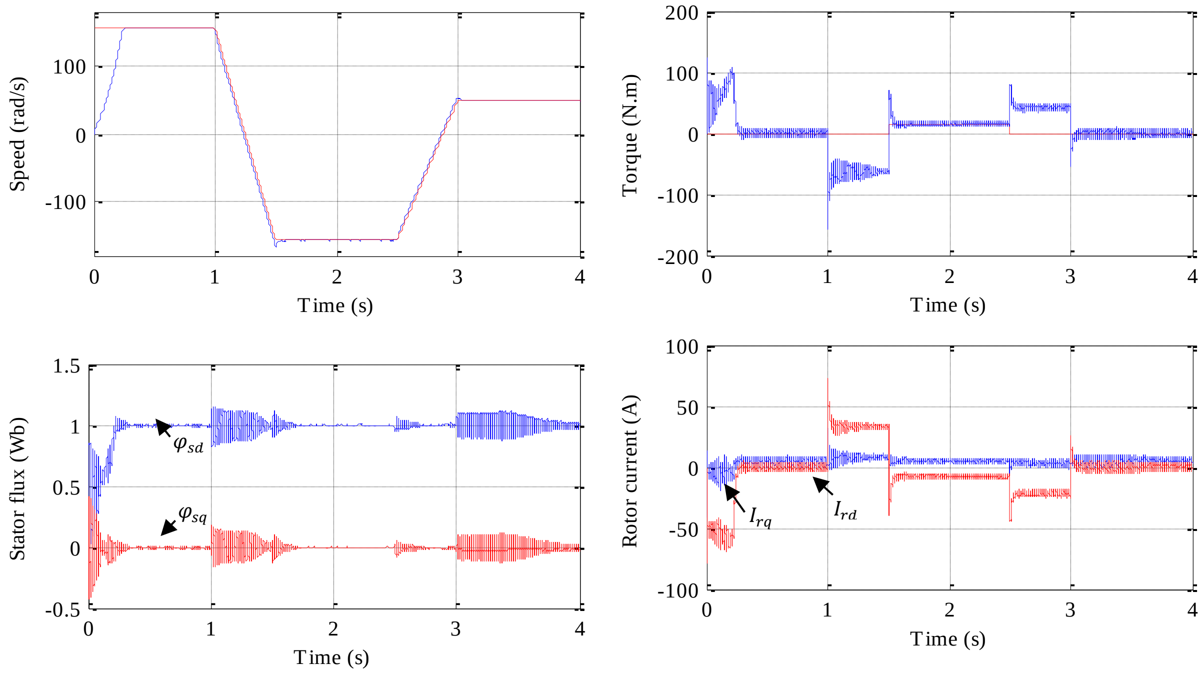

Fig. 10. Simulation results of IT2FBC of the DFIM when varying the speed

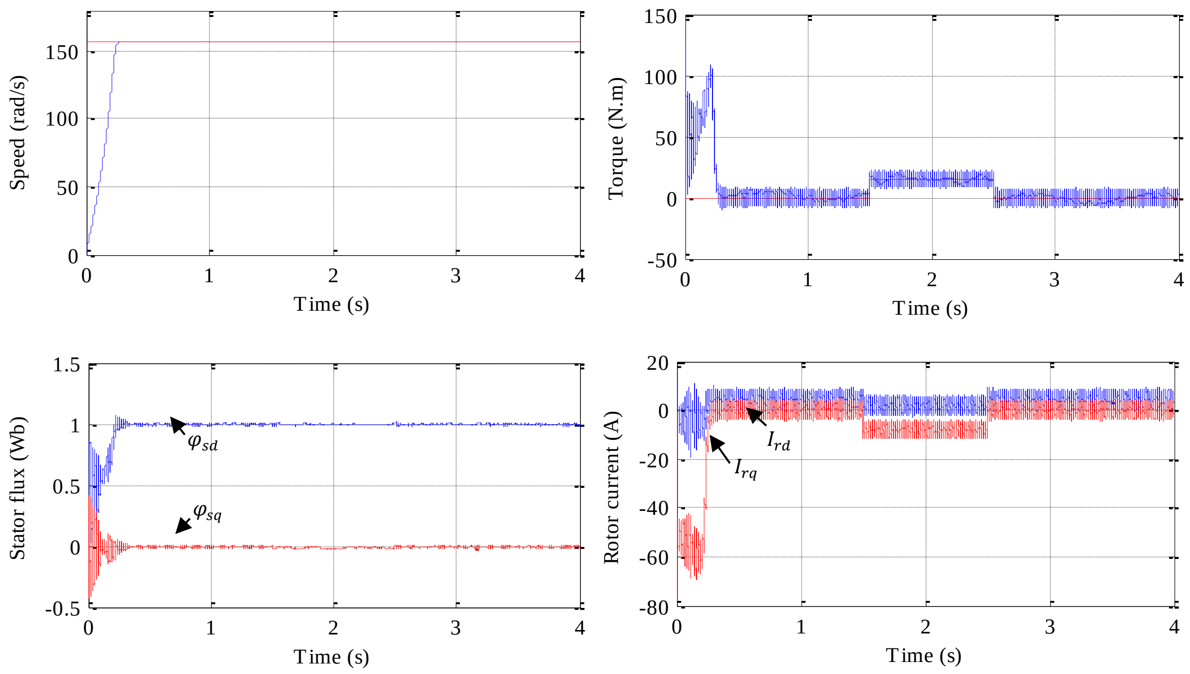

Fig. 11. Simulation results of IT2FBC of the DFIM when varying the rotor resistance

6. CONCLUSION

In this work, to improve the responses generated by the doubly fed induction motor, we have presented a new control law using the backstepping technique (based on stator flux orientation) and interval type-2 fuzzy logic. The hybrid control type 2 fuzzy-backstepping consists of replacing the regulator of speed applied to the backstepping control by regulator based on type-2 fuzzy logic.

The simulation results obtained for the various robustness tests (variation in the torque, variation in the direction of the speed, variation in the rotor resistance) clearly show the insensitivity of this new control, it can be seen that the speed follows its reference value without overshoot and the application of resistive torque hardly affects the desired rotational speed with a response time of 0.3s.

Author contributions: *research concept and design, A.H., R.R., A.Z.; Collection and/or assembly of data, A.H., R.R., A.Z.; Data analysis and interpretation, A.H., R.R., A.Z.; Writing the article, A.H., R.R., A.Z.; Critical revision of the article, A.H., R.R., A.Z.; Final approval of the article, A.H., R.R., A.Z.*

Declaration of competing interest: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

REFERENCES

1. Vicatos MS, Tegopoulos AJ. A doubly-fed induction machine differential drive model for automobiles. IEEE Transactions on Energy Conversion 2003; 18(2): 225-230. https://doi.org/10.1109/TEC.2003.811732
2. Holdsworth L, Wu XG, Ekanayake JB, Jenkins N. Comparison of fixed speed and doubly fed induction wind turbines during power system disturbances. IEE Proceedings - Generation, Transmission and Distribution 2003;150(3):343-352. https://doi.org/10.1049/ip-gtd:20030251.
3. Herizi A, Bouguerra A, Rouabhi R. Hybrid type-2 fuzzy sliding mode control of a doubly-fed induction machine (DFIM). AMSE Journals-IETA Publication, Advances in Modelling and Analysis C 2019; 74(2-4): 37-46. https://doi.org/10.18280/ama_c.742-401.
4. El Ouanjli N, Motahhir S, Derouich A, El Ghzizal A, Chebabhi A, Taoussi M. Improved DTC strategy of doubly fed induction motor using fuzzy logic controller. Energy Reports 2019; 5: 271-279. https://doi.org/10.1016/j.egyr.2019.02.001.
5. Leonhard W. Control of electrical drives. Springer-Verlag Berlin Heidelberg, 3rd edition, New York 2001.
6. Pyrhonen J, Hrabovcova V, Semken RS. Electrical machine drives control: an introduction. John Wiley & Sons Ltd 2016, First edition.
7. Li S, Yu X, Fridman L, Man Z, Wang X. Advances in variable structure systems and sliding mode control: theory and applications. Springer International Publishing AG 2018.
8. Derbel N, Ghommam J, Zhu Q. Applications of sliding mode control. Springer Science+Business Media Singapore 2017.
9. Krstic M, Kanellakopoulos I, Kokotovic PV. Nonlinear and adaptive control design. John Wiley & Sons, Inc. 1995.
10. Kokotovic PV. The joy of feedback: nonlinear and adaptive. IEEE Control systems Magazine 1992; 12(3): 7-17. https://doi.org/10.1109/37.165507.
11. Chaouch S, Herizi A, Serrai H, Nait Said M. Lyapunov and backstepping control design of induction motor system. 4th International Multi-Conference on Systems, Signals & Devices, Hammamet, Tunisia 2007.

12. El Azzaoui M, Mahmoudi H, Ed-dahmani C. Backstepping control of a doubly fed induction generator integrated to wind power system. International Conference on Electrical and Information Technologies, Tangier, Morocco 2016.
13. Bounar N, Boulkroune A, Boudjema F, M'Saad M, Farza M. Adaptive fuzzy vector control for a doubly-fed induction motor. Neurocomputing 2015;151(2): 756-769. https://doi.org/10.1016/j.neucom.2014.10.026.
14. Dualibe C, Verleysen M. Jespers PGA. Design of analog fuzzy logic controllers in CMOS technologies. Kluwer Academic Publishers, New York 2023.
15. Lowen R, Verschoren A. Foundations of generic optimization. Volume 2: Applications of fuzzy control, genetic algorithms and neural networks. Springer 2008.
16. Loukal K, Benalia L. Type-2 fuzzy logic control of a doubly-fed induction machine (DFIM). IAES International Journal of Artificial Intelligence (IJ-AI) 2015;4(4):139-152. https://doi.org/10.11591/ijai.v4.i4.pp139-152.
17. Herizi A, Bouguerra A, Rouabhi R. Backstepping control of a doubly-fed induction machine based on fuzzy controller. European Journal of Electrical Engineering 2018;20(5-6):645-657. http://dx.doi.org/10.3166/ejee.20.647-657.
18. Herizi A, Rouabhi R, Zemmit A. Comparative study of the performance of a sliding, sliding-fuzzy type 1 and a sliding-fuzzy type 2 control of a permanent magnet synchronous machine. Przegląd Elektrotechniczny 2022;98(11):21-29. https://doi.org/10.15199/48.2022.11.03.
19. Castillo O, Melin P. A review on the design and optimization of interval type-2 fuzzy controllers. Applied Soft Computing 2012;12(4):1267-1278. https://doi.org/10.1016/j.asoc.2011.12.010.
20. Juan R, Castillo O, Melin P, Díaz AR. A hybrid learning algorithm for a class of interval type-2 fuzzy neural networks. Information Sciences 2009; 179(13): 2175-2193. https://doi.org/10.1016/j.ins.2008.10.016.
21. Castillo O, Marroquín RM, Melin P, Valdez F, Soria J. Comparative study of bio-inspired algorithms applied to the optimization of type-1 and type-2 fuzzy controllers for an autonomous mobile robot. Information Sciences 2012;192:19-38. https://doi.org/10.1016/j.ins.2010.02.022.
22. Liang Q, Mendel JM. Interval type-2 fuzzy logic systems: theory and design. IEEE Transactions on Fuzzy Systems 2000;8(5):535-550. https://doi.org/10.1109/91.873577.
23. Mendel JM, John RI, Liu F. Interval type-2 fuzzy logic systems made simple. IEEE Transactions on Fuzzy Systems 2006;14(6):808-818. https://doi.org/10.1109/TFUZZ.2006.879986.
24. Mendel J. Uncertain rule-based fuzzy logic systems: introduction and new directions. Prentice-Hall 2001.

Dr. Abdelghafour HERIZI graduated with a degree in electronic engineering in 2006 from the University of M'sila in Algeria, and two years later, he earned a magister degree in electrical engineering from the Polytechnic Military School in Algiers. In 2021, the University of M'sila will award the Ph.D. in electrical engineering. He is currently Principal Investigator at the Electrical Engineering Laboratory, University of M'sila. His research interests include the modelling and control for nonlinear systems and renewable energy.
Contact: abdelghafour.herizi@univ-msila.dz

Dr. Riyadh ROUABHI works in the Department of Electrical Engineering at M'sila University. Obtained the Ph.D. Degree in electrical engineering, from University of Batna, Algeria in 2016. His current research area includes the control of induction machines and renewable energy.
Email: riyadh.rouabhi@univ-msila.dz