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Speed control of a doubly-fed induction machine based on fuzzy adaptive

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Abstract: In this paper, we are interested in the adaptive fuzzy control a technique has been studied and applied, namely adaptive fuzzy control based on theory of Lyapunov. The system based on the stability theory is used to approximate the gains k_e and k_{dce} to ensure the stability of the control in particular time, simulations results obtained by using MATLAB environment gives that the fuzzy adaptive control more robust, also it has superior dynamics performances. The results and test of robustness will be presented.

Keywords: adaptive fuzzy control; doubly fed induction machine; DFIM; fuzzy control; robust control; regulator; stability.

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1 Introduction

The asynchronous machine with double feed (DFIM) is very popular since it profit from certain advantages compared to all the other types at variable speed, sound use in the chains of electro mechanic conversion as an or engine knew a spectacular growth during in recent years. Indeed, it converter of energy used in order to rectify-undulate the alternating currents of the rotor has a fractional nominal output nominal of that of the generator, which reduces its cost by report/ratio with concurrent topology (Saidi and Naceri, 2016).

The DFIM is essentially non linear, due to the coupling between the flux and the electromagnetic torque. Vector control or field orientation control allows a decoupling between the torque and the flux (Payam and Kashiha, 2010; Chafaa et al., 2014).

The system of fuzzy logic aims to model human reasoning and thinking, the process with linguistic variables (Issaadi, 2017; Boukadoum and Bahi, 2017). They are very useful when the process to control with some uncertainties or unknown variables (Sundarapandian and Azar, 2016; Souli-Jbali and Hidri, 2015; Ramadan, 2017; Calcev et al., 1994).

However, in order to maintain consistent execution in the presence of true uncertainties, the use of adaptive control is, in most cases, inevitable. Fuzzy adaptive control has been the subject of intensive research during the last decade (Cao, 1997; Karnavas and Papadopoulos, 2004; Chen et al., 1999; Chih and Chun, 2004).

Therefore, the combination of the study of adaptability and uncertainty has allowed researchers to derive adaptive fuzzy controllers (Chekkouri et al., 2003; Ramadan et al., 2015).

Several adaptive fuzzy control schemes have been proposed for complex systems in these adaptive schemes, the study of stability is based on the Lyapunov approach (Fischle and Schroder, 1999; Yusupbekov et al., 2016). An adaptive fuzzy control approach can be used: the direct approach is based on the adaptation mechanism. In the direct approach (Ho and Cheng, 2009), the adaptation system is used to estimate the gains of the PI-fuzzy and the control law is obtained from this PI-fuzzy controller.

Despite the dynamic capabilities and their practical implementation, the first PI-fuzzy suffered from lack of stability analysis, that is to say the stability of the closed loop is not guaranteed (Sarala et al., 2016; Furuhashi et al., 1998; Faquir et al., 2016). Recently, a large class of adaptive fuzzy systems, which use the fuzzy systems of Mamdani or TS was developed to control nonlinear processes, and stability has been guaranteed in the sense of the Lyapunov theory.

Treatment in this paper adaptive fuzzy control based on stability theory to recalculate real-time PI-fuzzy gains, we will develop a new order strategy is: adaptive fuzzy control based on the theory of Lyapunov proposed in order to solve the problems of determination of the gains of the pi-fuzzy whose aim to ensure the stability of the control and to increase the robustness regardless of the parametric variation.

2 Adaptive fuzzy control based on Lyapunov theory

Today, there are a number of studies on the stability of fuzzy systems. However, restrictive because of nonexistence tools appropriate. To do this, the fuzzy controller being nonlinear, we have to do use of nonlinear methods, such as the Lyapunov method, the theory of hyper stability or the criterion of Popov. Most of these methods are quite limiting, providing only sufficient conditions for stability in a domain restricted.

For adaptive fuzzy control based on the Lyapunov theory, we follow two steps. The first is devoted to the design of a PI-fuzzy controller. The second is to define the methodology for determining the gains of a fuzzy regulator based on the Lyapunov theory. The control applied to the dual power asynchronous machine is provided by a PI-fuzzy controller.

We proposed a new adaptive fuzzy control strategy based on the theory of Lyapunov to determine the gains of K_e and K_{dce} (normalisation), which can be applied for a large class of nonlinear systems. It combines the advantages of two robust techniques and which are the control by the fuzzy logic and the control adaptive (Laamayad et al., 2012; Chen et al., 1999).

2.1 Control law of a PI-fuzzy controller

We consider a nonlinear system whose dynamic equation of the command is described in the following form:

$$T_{em}^{*}(t) = T_{em}^{*}(t-1) + K_{dce} dT_{nem} \tag{1}$$

2.2 Fuzzification

The error between the reference signal and the process serves to act directly (the gains of the mad regulator are recalculated in particular time as a function of this error and the response of the regulator itself and gains and coefficients of adaptation). The speed error denoted $e(t)$ is defined by:

$$e(t) = \omega_{ref} - \omega_r(t) \tag{2}$$

The derivative of the speed error noted $\frac{de(t)}{dt}$ is approximated by:

$$\frac{de(t)}{dt} = \dot{e}(t) \approx \frac{de(t+1) - e(t)}{T_e} \tag{3}$$

T_e: Being the sampling period.

The error and the derivative of the error are adapted as follows:

$$e(t) = K_e e_n(t) \tag{4}$$

$$e(t) = K_e e_n(t) \tag{5}$$

2.3 Inference table

Once the fuzzy presentation stage is complete, the gains estimated by the adjustment mechanism which uses the Lyapunov theory are sent to the fuzzy regulator to construct the output $dT_{nem}(t)$ Therefore, the fuzzy regulator rule takes the following form:

Table 1 Inference matrix of fuzzy rules

dT_{nem}		e_n				
		NB	*NM*	*Z*	*PM*	*PB*
$\frac{de_n}{dt}$	NB	NB	NB	NM	NVS	Z
	NM	NB	NM	NVS	Z	Ps
	Z	NM	NVS	Z	PS	PM
	PM	NVS	Z	PS	PM	PB
	PB	Z	PS	PM	PB	PB

2.4 *Defuzzification*

For the defuzzification, it uses the method of the centre of gravity presented previously, we obtain:

$$dT_{nem}(t)=\frac{\sum_{j=1}^{25}=1\mu_{A1J}\left(e_n(t)\right)\mu_{A2J}\left(\frac{de_n(t)}{dt}\right)C_J S_J}{\sum_{j=1}^{25}\mu_{A1J}\left(e_n(t)\right)\mu_{A2J}\left(\frac{de_n(t)}{dt}\right)C_J S_J} \tag{6}$$

Such as:

S_J is the surface of belonging function the decision of the J^{th} rule

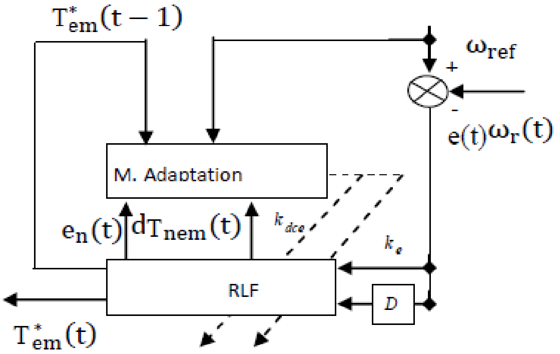
C_J is the abscissa of centre of gravity of belonging function the decision of J^{th} rule

J is the total number of fuzzy rules.

3 Schematic diagram

To minimise the instantaneous error between the actual speed of the machine DFIM and that of the reference speed we recalculate in particular time the gains k_e and k_{dce} of the premises and the consequences by the application of an adaptation algorithm of study type stability of control in the sense of Lyapunov (Laamayad et al., 2012; Chen et al., 1999).

Figure 1 Structure of adaptive fuzzy control based on the Lyapunov theory



4 Determining the gain of a PI-fuzzy controller

4.1 Study of the adaptation mechanism

There are many notions of stability for dynamic systems. We will study the following notion:

- Asymptotic stability: Lyapunov stability + the trajectories tend asymptotically towards 0.

We consider a nonlinear system whose mechanical equation of the machine DFIM is described in the following form:

$$\frac{J}{P}\frac{d\omega_r(t)}{dt} = T_e - T_r - \frac{f_r}{P}\omega_r(t) \tag{7}$$

The equation can be written as follows:

$$\dot{\omega}_r(t) = \frac{d\omega_r(t)}{dt} = -a_p\omega_r(t) + b_pT_e(t) - d_pT_r \tag{8}$$

Such as a_p, b_p, d_p are constants of the machine DFIM. In adaptive fuzzy control based on theory of Lyapunov stability, the control $T_{em}^*(t)$ is equalled by an electromagnetic torque such as.

$$T_e(t) = T_{em}^*(t) = T_{em}^*(t-1) + K_{dce}dT_{nem}(t)$$

By replacing equation (1) in equation (6), we obtain the following form:

$$\dot{\omega}_r(t) = -a_p\omega_r(t) + b_pT_{em}^*(t-1) + b_pK_{dce}dT_{nem}(t) - d_pC_r \tag{9}$$

The error $e(t)$ and his derivative $\frac{de(t)}{dt}$ are used to construct the base of the adaptation mechanism of the adaptive fuzzy controller. Each size of the adaptation mechanism is of the following form:

The speed error denoted $e(t)$ is defined by:

$$e(t) = \omega_{ref} - \omega_r(t) \tag{10}$$

The derivative of the speed error noted $\frac{de(t)}{dt}$ is approximated by:

$$\dot{e}(t) = \frac{de(t)}{dt} = \frac{d\omega_{ref}(t)}{dt} - \frac{d\omega_r(t)}{dt} \tag{11}$$

Then, one obtains as follows:

$$\frac{de(t)}{dt} = \dot{e}(t) = -a_p\omega_r(t) + b_pT_{em}^*(t-1) + b_pK_{dce}dT_{nem}(t) - d_pT_r \tag{12}$$

Since:

$$\frac{d\omega_{ref}(t)}{dt} \tag{13}$$

5 Analysis of the stability of the proposed control

5.1 Function of Lyapunov candidate

Function of Lyapunov can be considered as a function of error and the variation of the gains. This is a decreasing function along the trajectories of the system. We consider a Lyapunov candidate function:

$$V = \frac{1}{2}\left(e^2 + \frac{1}{\gamma_1}k_e^2 + \frac{1}{\gamma_2}k_{dce}^2\right) \quad \gamma_1 > 0 \quad \text{and} \quad \gamma_2 > 0 \tag{14}$$

The derivative of the Lyapunov functions with respect to real time:

$$\frac{dV}{dt} = e\frac{de}{dt} + \frac{k_e}{\gamma_1}\frac{dk_e}{dt} + \frac{k_{dce}}{\gamma_2}\frac{dk_{dce}}{dt} \tag{15}$$

The following expression can be obtained:

$$\frac{dV}{dt} = e\left(a_p\omega_r(t) - b_pT_{em}^*(t-1) - b_pk_{dce}dT_{nem}(t) + d_pT_r\right) + \frac{k_e}{\gamma_1}\frac{dk_e}{dt} + \frac{k_{dce}}{\gamma_2}\frac{dk_{dce}}{dt} \tag{16}$$

We note that we can replace the necessary expression of error *e*(*t*) by the form next error $e(t) = k_e e_n(t)$ in the derivative of the Lyapunov function. So

$$\frac{dV}{dt} = -a_pk_e^2e_n^2 + \frac{k_e}{\gamma_1}\left(\gamma_1 e_n A + \frac{dk_e}{dt}\right) - \frac{k_{dce}}{\gamma_2}\left(\gamma_2 b_p k_e e_n dT_{nem}(t) - \frac{dk_{dce}}{dt}\right) \tag{17}$$

Such as:

$$A = \left|(a_p\omega_{ref} - b_pT_{em}^*(t-1)\right| \tag{18}$$

The gains of a fuzzy regulator are to be defined from a single necessary and sufficient condition for existence of the stability regime in the sense from Lyapunov.

$$\frac{dV}{dt} < 0 \tag{19}$$

The inequality is verified by imposing the following adaptation law:

$$\frac{dk_e}{dt} = -\gamma_1 e_n A \tag{20}$$

$$\frac{dk_{dce}}{dt} = \gamma_2 b_p k_e e_n dT_{nem} \tag{21}$$

Finally we have come to the expression of the derivative:

$$\frac{dV}{dt} = -a_p k_e^2 e_n^2$$

The form of the Lyapunov function is proposed to determine the PI-fuzzy gains which ensure a convergence of the actual speed of the DFIM towards its reference value.

Adaptation gains are recalculated in particular time in the purpose of imposing desired stability on the controlled system that is to say the speed of adjustment at the level of the assembly

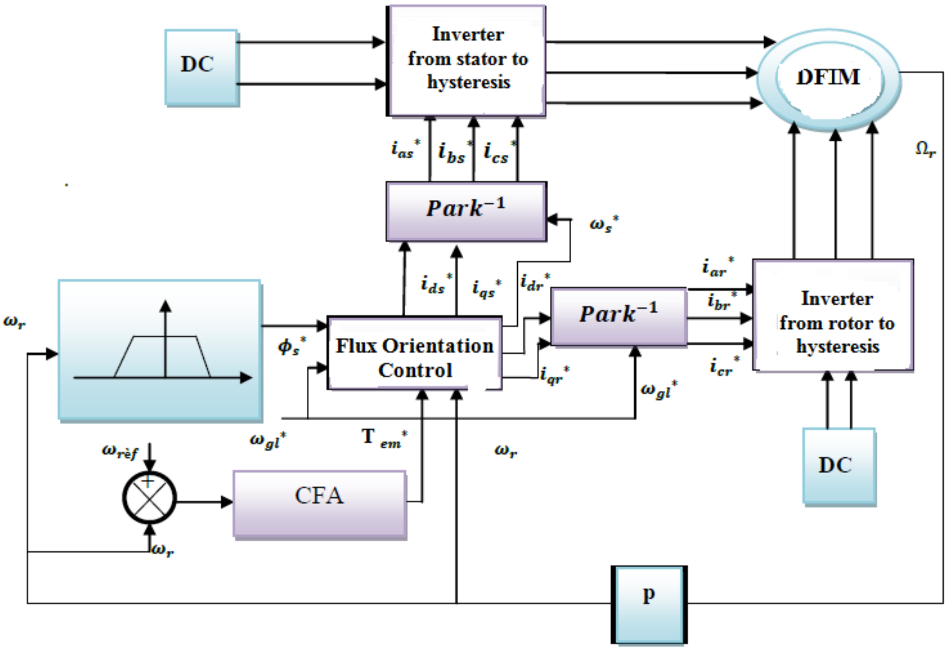
PI-fuzzy controller, and the DFIM machine in the transitional regime. So, for the speed loop, the parameters of the Lyapunov function are chosen to ensure: the derivative of the Lyapunov candidate always negative [equation(14)], as well as an accuracy of speed control.

6 Application for doubly fed induction machine

For the adjustment of the speed of a DFIM by the adaptive fuzzy control based on the theory of Lyapunov, the following method is followed.

From the reference speed and the actual speed, the adaptive fuzzy controller provides the torque $T_{em}^*(t)$. A transformation of park (dq-abc) makes it possible to calculate the current stator of references. These currents are compared with real currents to order of each inverted.

Figure 2 Structure of speed control by adaptive fuzzy control method based on the Lyapunov theory (see online version for colours)



To adjust the speed, use the output of the fuzzy controller T_{em}^*, as well as the adjustment of gains to ensure stability of control. In our application, we used a PI-Fuzzy. The first concerns speed, where we assigned five membership functions to each entry of the model. Figure 2 illustrates the speed control structure of a doubly fed induction machine by applying the method of fuzzy adaptive control based on theory from Lyapunov.

7 Simulation results

It appears, following the various results obtained, that the performance of speed control by the application of adaptive fuzzy control with the stability of control is very satisfactory. The coefficients γ_1, γ_2 have respectively 0.005 and 70 respectively. so the initial values of gains k_e, k_{dce} are respectively 7 and 5.8, To demonstrate the adaptability of the proposed control scheme to parametric variations, we introduce parametric variations on the resistance rotor, as well as the moment of inertia at the instant $t = 1$s. Resistance and moment of inertia are increased by 150%, and then the resistance and moment of inertia are decreased of 50%. The responses obtained are shown in Figures 5–6. It is clear that this parametric variation did not affect the speed control performance, which proves the efficiency of the control algorithm used.

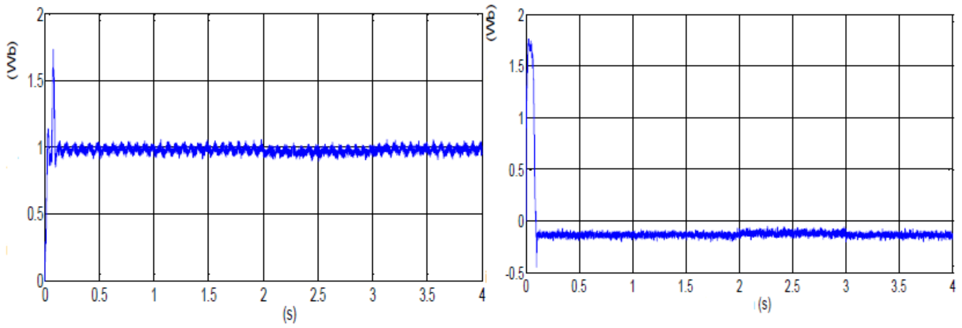
7.1 *Introduction of a load torque*

Figures 4(a) and 4(b) show the performance of the speed control of the double-feed asynchronous machine for a set point of 100 rad/s with a variation of the load, speed takes the reference speed approach though the presence of disturbances of charge. The response time is in the order of 0.1s. The overrun is zero.

7.2 *Change of set point and reversal of direction of rotation*

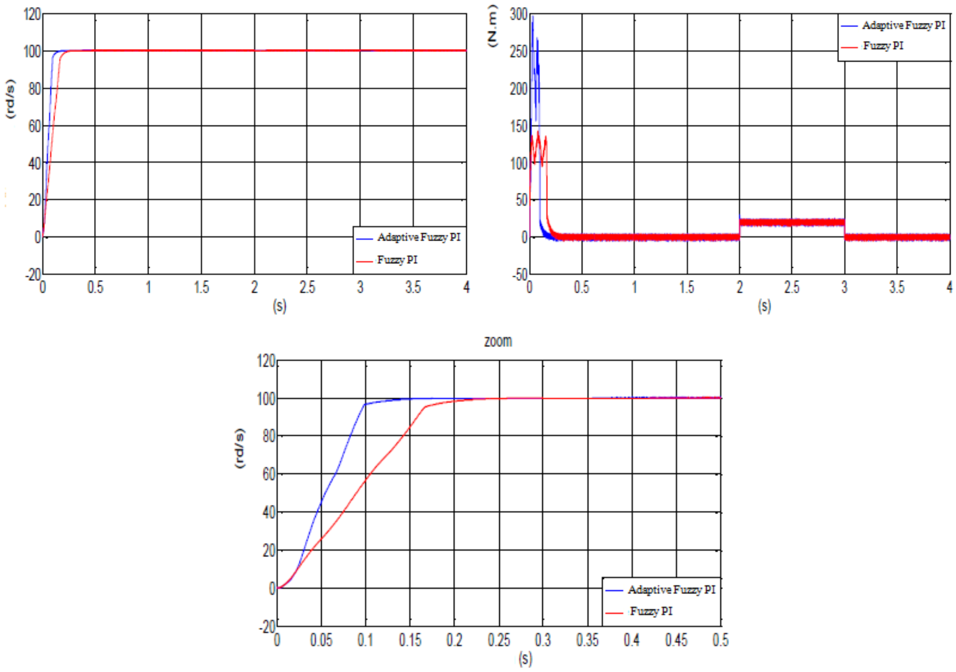
Applying an inversion of direction of rotation of –100 rd/s at time $t = 2$(s), we obtain the simulation results represented by the Figure 4.

Figure 3 Dynamic machine response with PI-fuzzy control during the introduction of a load torque of ($t_l = 20$ N · m) at time t = 2 (s), (a) components of direct stator flux φ_{ds} and in quadrature φ_{qs} (b) dynamic response of speed and electromagnetic torque (c) evolution of the fuzzy gains (k_e, k_{dce}) (see online version for colours)

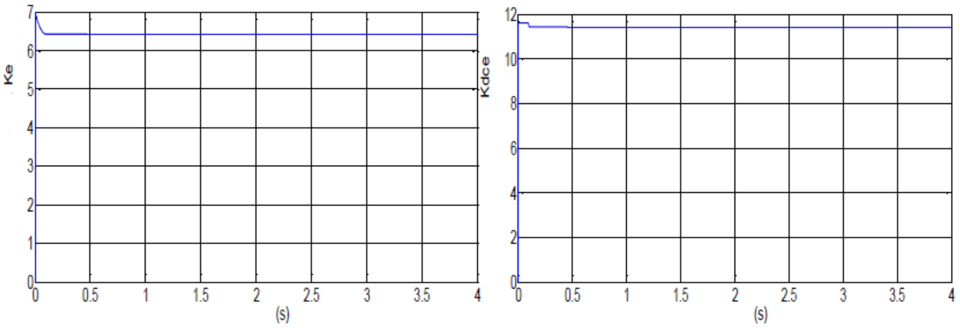


(a)

Figure 3 Dynamic machine response with PI-fuzzy control during the introduction of a load torque of ($t_l = 20$ N · m) at time t = 2 (s), (a) components of direct stator flux φ_{ds} and in quadrature φ_{qs} (b) dynamic response of speed and electromagnetic torque (c) evolution of the fuzzy gains (k_e, k_{dce}) (continued) (see online version for colours)



(b)



(c)

7.3 *Tests of robustness*

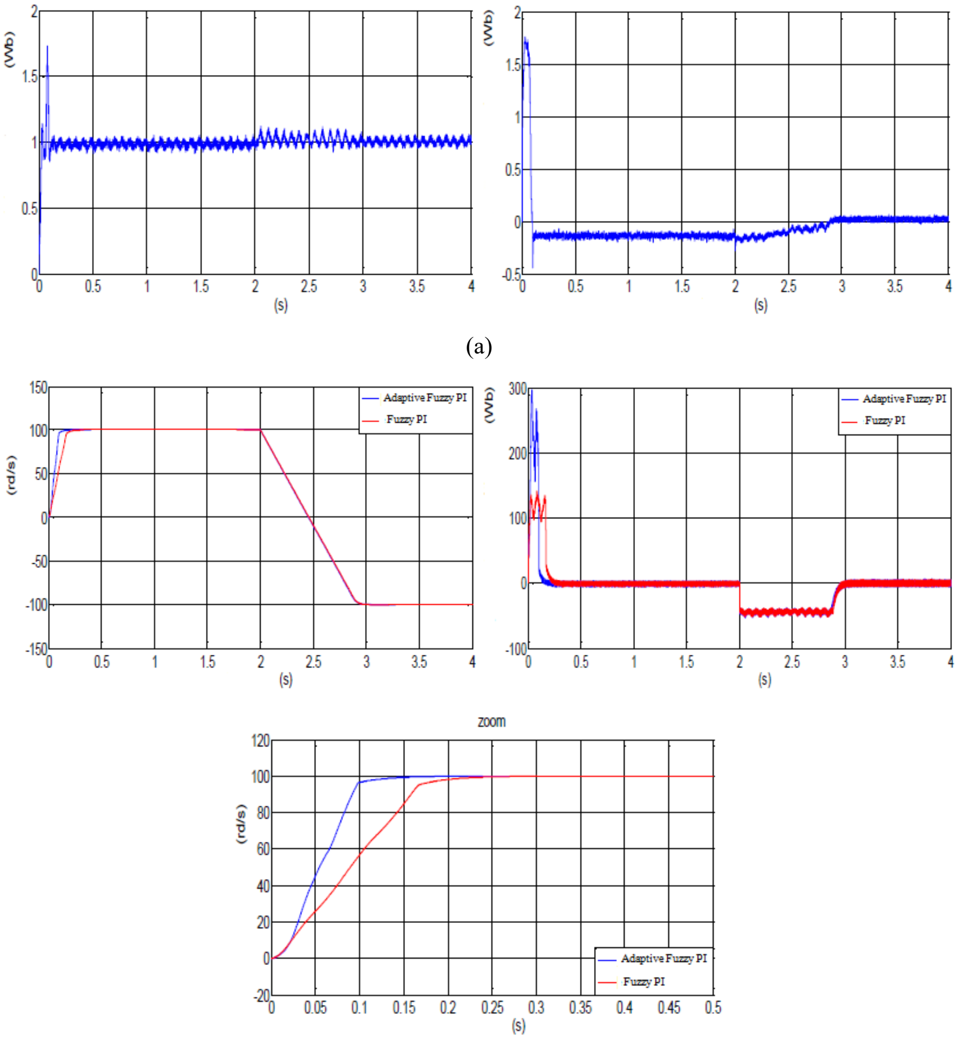
7.3.1 *Robustness with respect to variation in rotor resistance*

The test consists of a variation of the rotor resistance in a range of 50% and 150%. The speed and the electromagnetic torque, the stator fluxes direct and quadrature as well as the evolution of the fuzzy gains.

7.3.2 Robustness-with respect to variation of inertia

The robustness of control is its ability to overcome the uncertainty control. The behaviour of the regulation with respect to the variations of parameters of the DFIM, varying the moment of inertia J in a range of 50% and 150% of their nominal value. Speed and torque electromagnetic, direct stator and quadrature fluxes as well as the evolution of the fuzzy gains.

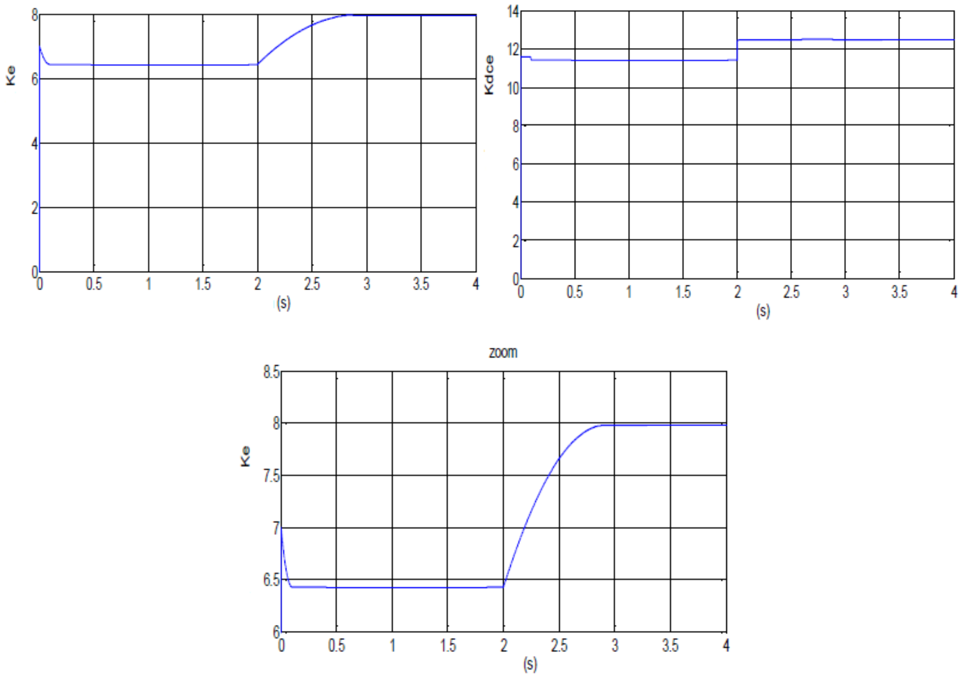
Figure 4 Dynamic machine response with adaptive fuzzy control applied when the direction of rotation is reversed at time t = 2(s), (a) components of direct rotor φ_{ds} and in quadrature φ_{qs} (b) dynamic response of speed and electromagnetic torque (c) evolution of the fuzzy gains (k_e, k_{dce}) (see online version for colours)



(a)

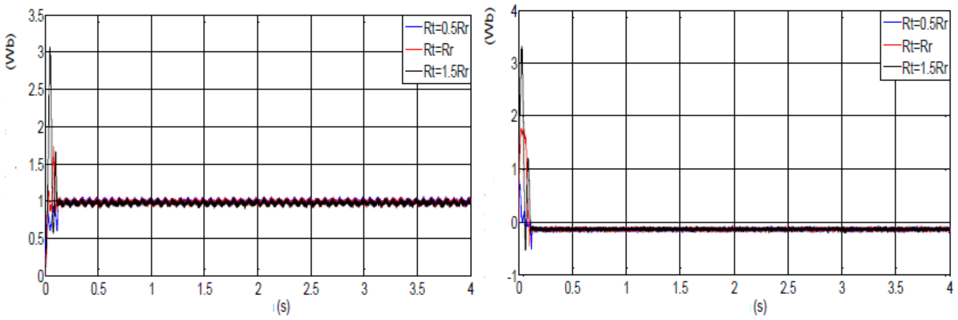
(b)

Figure 4 Dynamic machine response with adaptive fuzzy control applied when the direction of rotation is reversed at time $t = 2$(s), (a) components of direct rotor φ_{ds} and in quadrature φ_{qs} (b) dynamic response of speed and electromagnetic torque (c) evolution of the fuzzy gains (k_e, k_{dce}) (continued) (see online version for colours)



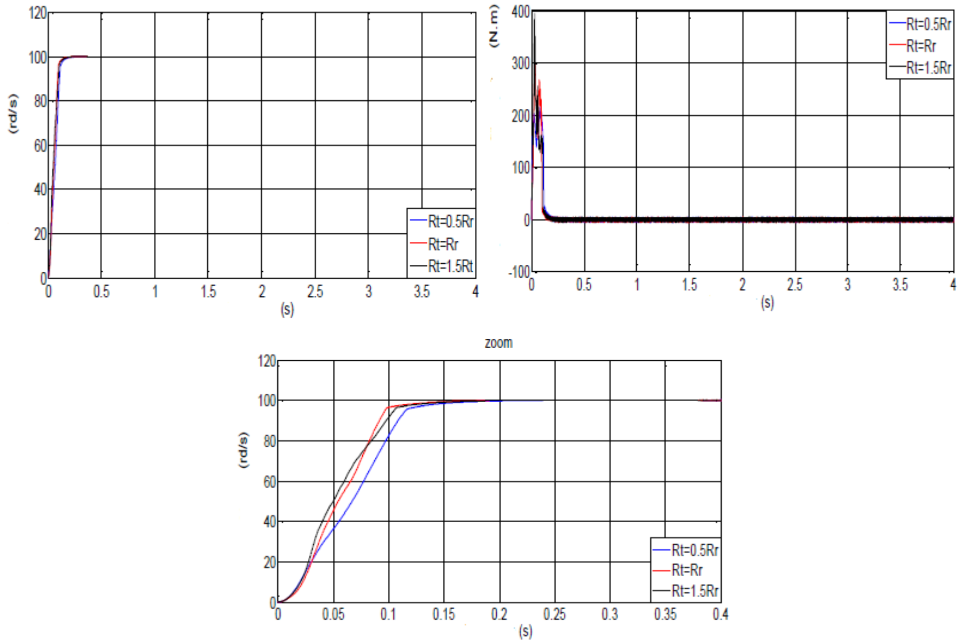
(c)

Figure 5 Dynamic response of the machine with application of the fuzzy control adaptive in the robustness test with respect to the rotor resistance R_r, (a) components of direct stator flux φ_{ds} and in quadrature φ_{qs} (b) dynamic response of speed and electromagnetic torque (c) evolution of the fuzzy gains (k_e, k_{dce}) (see online version for colours)

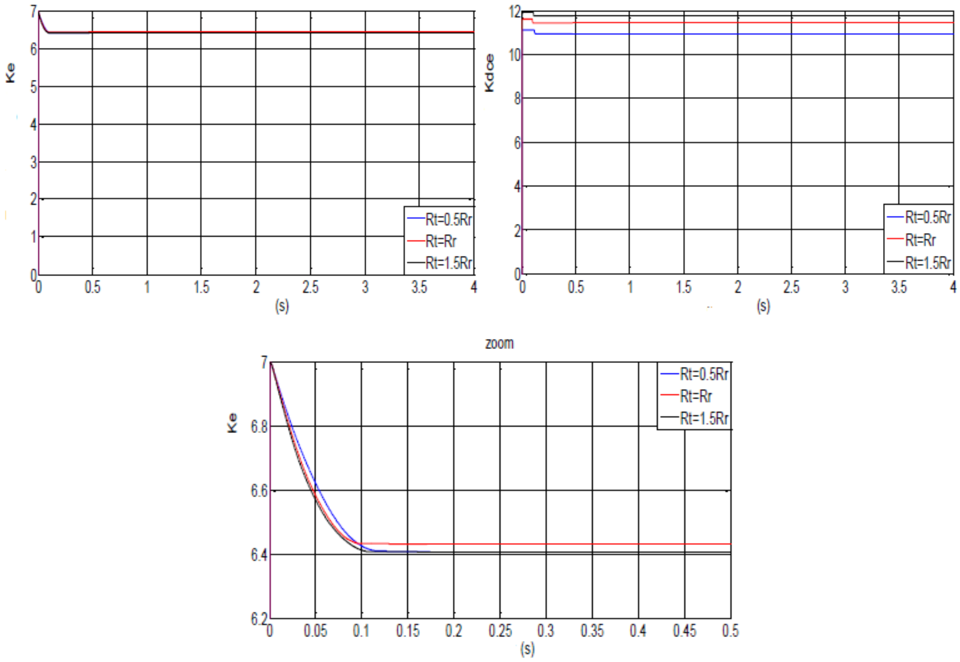


(a)

Figure 5 Dynamic response of the machine with application of the fuzzy control adaptive in the robustness test with respect to the rotor resistance R_r, (a) components of direct stator flux φ_{ds} and in quadrature φ_{qs} (b) dynamic response of speed and electromagnetic torque (c) evolution of the fuzzy gains (k_e, k_{dce}) (continued) (see online version for colours)

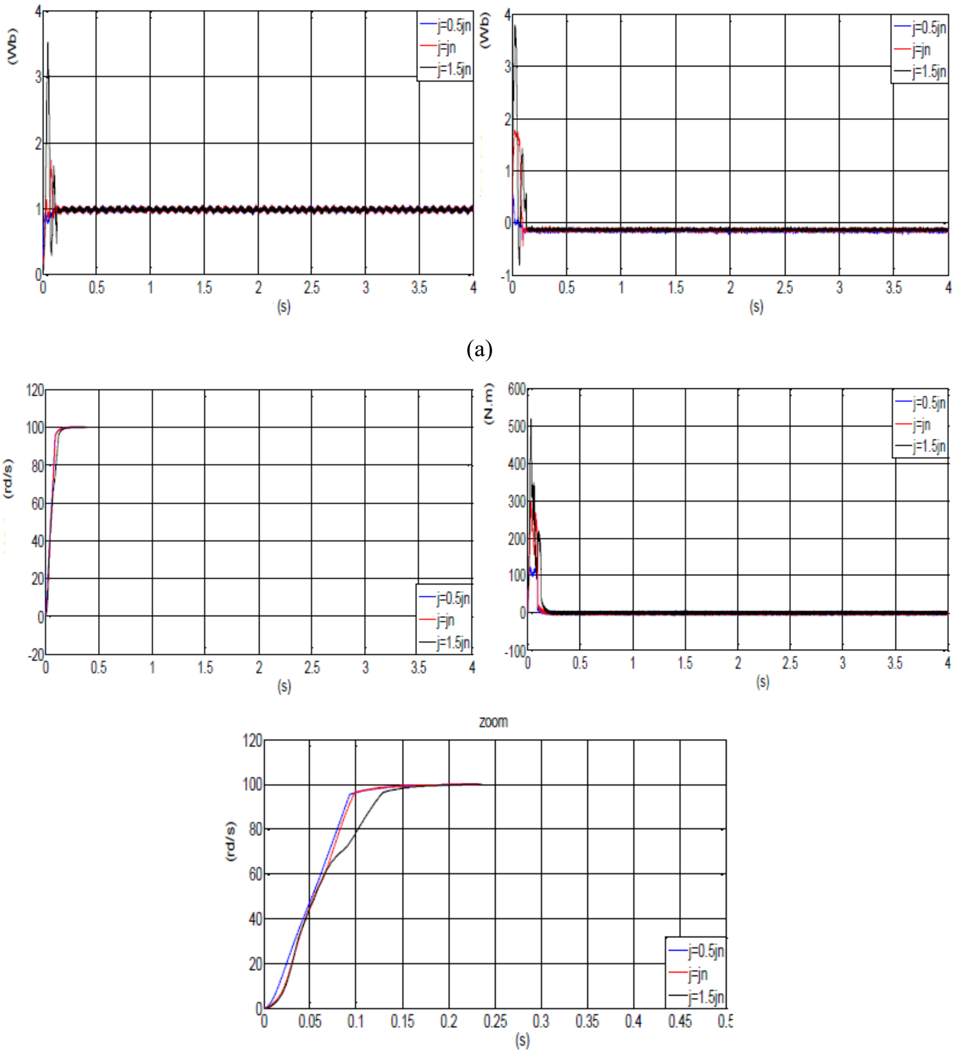


(b)



(c)

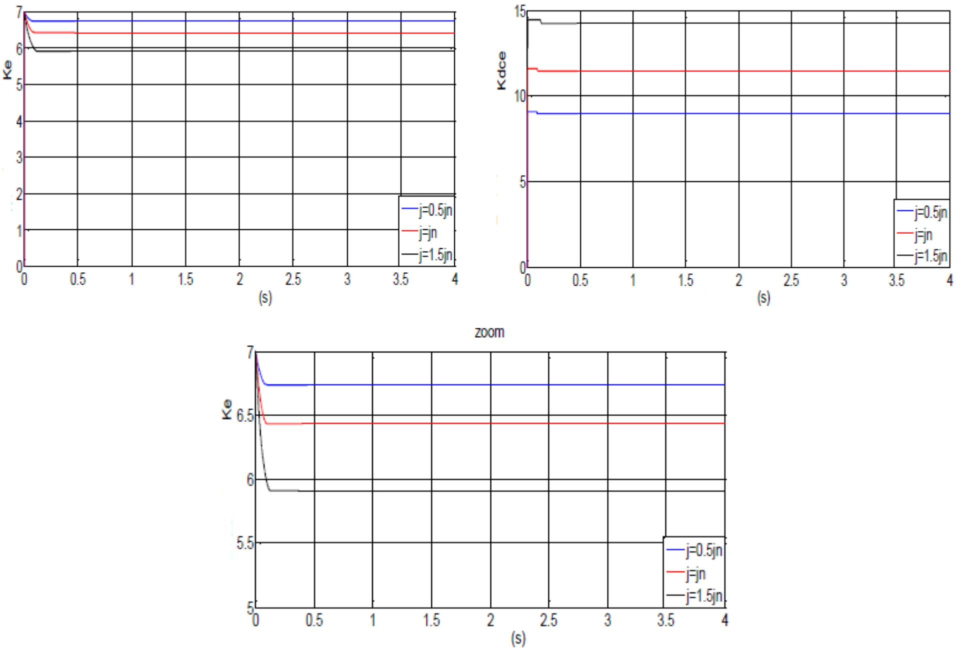
Figure 6 Dynamic response of the machine with application of the fuzzy control adaptive during the robustness test with respect to moment of inertia J, (a) components of direct stator flux φ_{ds} and in quadrature φ_{qs} (b) dynamic response of speed and electromagnetic torque (c) evolution of the fuzzy gains (k_e, k_{dce}) (see online version for colours)



(a)

(b)

Figure 6 Dynamic response of the machine with application of the fuzzy control adaptive during the robustness test with respect to moment of inertia J, (a) components of direct stator flux φ_{ds} and in quadrature φ_{qs} (b) dynamic response of speed and electromagnetic torque (c) evolution of the fuzzy gains (k$_e$, k$_{dce}$) (continued) (see online version for colours)



(c)

8 Conclusions

The obtained results as well as the various tests have shown that this technique good performance in the presence of load disturbances and reversing the direction of travel, the speed follows its reference, The stator flux follows its reference value along the axis d with a zero component along the axis q. An increase in the electromagnetic torque in the presence of the Resistive torque which leads to a good acceleration of the motor.

PI-fuzzy control with gain adaptation k_e and k_{dce} by the theory of Lyapunov is also tested for parametric variations of the system. The results have enabled us to judge that this new ordering strategy strong robustness in the presence of variations.

The simulation results presented show that the performances of this approach outperform vector control because of the speed of its dynamics and its robustness. Lastly, it therefore seemed natural to construct an adaptation mechanism for adaptive fuzzy gains that combine the concepts of fuzzy inference systems, that for have an adaptive fuzzy approach that can improve the stability of the control.

Comparisons of the results presented during this work led us to conclude that the adaptive fuzzy regulator leads to better performance (continuation and robustness) that the other controllers treated because of its robustness, its speed (time of response) and stability of coping mechanism that allow it to give gains correct and to avoid the problem of the test-error method.

References

Boukadoum, A. and Bahi, T. (2017) 'Power quality improvement using fuzzy logic controlled voltage source PWM rectifiers', *Int. J. of Intelligent Engineering Informatics*, Vol. 5, No. 3, pp.242–252.

Calcev, G., Greco, C. and Bona, B. (1994) 'Fuzzy controller synthesis using sliding mode approach', *Proceeding of the First International Joint Conference of the North American Fuzzy Information Processing Society Biannual Conference, and the NASA Joint Technology*, IEEE, pp255–258.

Cao, M.T. (1997) *Commande numérique de machines asynchrones par logique floue*, thèse de Philosophie doctorat faculté des études supérieure de l'université Laval.

Chafaa, K.H., Khireddine, M.S., Slimane, N. and Ghanai, M. (2014) 'Fuzzy estimation based on type-2 fuzzy logic for adaptive Control', *Proceedings of IEEE International Conference on Computer Applications & Research (WSCAR)*, Sousse, Tunisia.

Chekkouri, M.R., Lopez, J.C.I., Rubira, E.A. and Martinez, L. (2003) 'Fuzzy adaptive control of an induction motor drive', *Automatika*, Vol. 3, No. 4, pp.113–122.

Chen, B., Zhang, Y., Yen, J. and Zhao, W. (1999) 'Fuzzy adaptive connection admission control for real-time applications in ATM-based heterogeneous networks', *Journal of Intelligent and Fuzzy Systems*, Vol. 7, No. 2, pp.125–135.

Chih, M.L. and Chun, F.H. (2004) 'Adaptive fuzzy sliding-mode control for induction servomotor systems', *IEEE Transactions on Energy Conversion*, Vol. 19, No. 2, pp.362–368.

Faquir, S., Yahyaouy, A., Tairi, H. and Sabor, J. (2016) 'Energy management in a hybrid PV/wind/battery system using a type-1 fuzzy logic computer algorithm', *Int. J. of Intelligent Engineering Informatics*, Vol. 4, Nos. 3/4, pp.229–244.

Fischle, K. and Schroder, D. (1999) 'An improved stable adaptive fuzzy control method', *IEEE Trans on Fuzzy Systems*, Vol. 7, No. 1, pp.27–40.

Furuhashi, T., Kakami, H. and Pedrycz, W. (1998) 'A stability analysis of fuzzy control system using a generalized fuzzy Petri net model', 0-7803-4863-X/98 $10.0001998 IEEE.

Ho, H.F. and Cheng, K.W.A. (2009) 'Position control of induction motor using indirect adaptive fuzzy sliding mode control', *IEEE 3rd International Conference on Power Electronics Systems and Applications*, pp.1–5.

Issaadi, W. (2017) 'Control of a photovoltaic system by fuzzy logic, comparative studies with conventional controls: results, improvements and perspectives', *Int. J. of Intelligent Engineering Informatics*, Vol. 5, No. 3, pp.206–224.

Karnavas, Y.L. and Papadopoulos, D.P. (2004) 'Excitation control of a synchronous machine using polynomial neural networks', *Journal of Electrical Engineering*, Vol. 55, Nos. 7–8, pp.169–179.

Laamayad, T., Naceri, F. and Abdessemed, R. (2012) 'Fuzzy adaptive controller based on the lyapunov theory for control of the dual star induction machine', *Journal of Electrical Engineering*, Vol. 12, No. 2, pp.47–54.

Payam, F. and Kashiha, H. (2010) 'Robust speed sensorless control of doubly-fed induction machine based on input-output feedback linearization control using a sliding-mode observer', *World Appl. Sci. J.*, Vol. 10, No. 11, pp.1392–1400.

Ramadan, R.A. (2017) 'Fuzzy brain storming optimisation algorithm', *Int. J. of Intelligent Engineering Informatics*, Vol. 5, No. 1, pp.67–79.

Ramadan, R.A., El Samadony, B.R., and Darwish, N.M. (2015) 'Fuzzy-based centroid localisation in WSNs', *Int. J. of Intelligent Engineering Informatics*, Vol. 3, No. 4, pp.293–312.

Saidi, A. and Naceri, F. (2016) 'Comparative study between sliding mode controller and fuzzy sliding mode controller in a speed control for doubly fed induction motor', *Proceedings of IEEE International Conference on Control Engineering and Information Technology (CEIT)*, Tunisia, pp.1–6.

Sarala, R., Zayaraz, G. and Vijayalakshmi, V. (2016) 'Fuzzy cognitive map-based reasoning for prediction of multi-stage attacks in risk assessment', *Int. J. of Intelligent Engineering Informatics*, Vol. 4, No. 2, pp.151–167.

Souli-Jbali, R. and Hidri, M.S. (2015) 'A cloud-based optimal fuzzy clustering of distributed data', *Int. J. of Intelligent Engineering Informatics*, Vol. 3, No. 1, pp.42–56.

Sundarapandian, V. and Azar, A.T. (2016) 'Takagi-Sugeno fuzzy logic controller for Liu-Chen four-scroll chaotic system', *Int. J. of Intelligent Engineering Informatics*, Vol. 4, No. 2, pp.135–150.

Yusupbekov, N.R., Marakhimov, A.R., Igamberdiev, H.Z. and Umarov, S.X. (2016) 'An adaptive fuzzy-logic traffic control system in conditions of saturated transport stream', *The Scientific World Journal*, Article ID 6719459, 9pp.

Appendix

Rated data of the simulated doubly fed induction machine

Rated values: 0.8 KW; 220/380 V – 50 Hz; 3.8/2.2 A, 1,420 rpm.

Rated parameters:

$R_s = 1.2\ \Omega$
$R_r = 1.8\ \Omega$
$L_s = 0.1554$ H
$L_r = 0.\ 1568$ H
$M = 0.15$ H
$P = 2$

Mechanical constants:

$J = 0.02$ Kg.m2
$f = 0.001$ I.S.

Adaptive fuzzy mechanism parameters:

$\gamma_1 = 0.005$
$\gamma_2 = 70$

Parameters of the PI-fuzzy controller used:

$k_e = 7$
$k_{de} = 0.01$
$k_{dce} = 5.8$