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DSP improvement of a vector speed induction motor control with a RST and adaptive fuzzy controller

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ABSTRACT

The aim of this work is to improve the dynamics and to overcome the limitation of conventional fixed parameters PI controller used in induction motor (IM) field-oriented control (FOC). This study presents and implements a RST and an adaptive fuzzy controller (AFC) to enhance variable speed control. Theoretical background of theses controllers is outlined and then experimental results are presented. Practical implementation has been realized on a board with a 1.1 KW IM supplied by 10 KHz space vector pulse width modulation current regulated inverter used as power amplifier consisted of 300V, 10A IGBT and Matlab/Simulink environment. Test benches have been established under different operating conditions in order to evaluate and compare the performances of the PI, IP, and polynomial RST and adaptive fuzzy controllers. Parameter variations for the rotor and the inertia moment variation were done in order to compare and verify the robustness of each controller. High dynamic performances and robustness against parameters variation were obtained with the use of both RST and AFC.

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1. INTRODUCTION

IM is the most potential candidate in the industrial field working in difficult environments. It is highly recommended and presents many advantages, such as being robust, simple and relatively cheap with high mass torque and absence of brush collector system [1]. The main applications are pumping, ventilation and machine tools. The field-oriented control (FOC) provides high level performance drive and permits a decoupled control of torque and flux [2]. Nowadays, the use of FOC with IM becomes the most used strategy. IM becomes a superior choice over direct current (DC) drives.

PI controller is widely used because of its implantation simplicity but its performances are degraded under external disturbances, parameters variations and temperature changes [3], [4]. The dynamic torque response is deteriorated due to the differences between measured and actual motor parameters [5]-[6]. Many researchers have focused on developing accurate mathematical models and different model-free methods have been developed [7], [8]. These methods include sliding mode control (SMC) [4], [9], [10], back-stepping control [11]-[13], the passivity based approaches [14],neural networks (NNs) [15]-[17] and fuzzy control (FC) system [18]-[21]. However, NNs learning algorithms are in general still complex and increases the computational burden of NNs.

Parameter adaptation with fuzzy logic is one option to improve the PI controllers [22]. This can be achieved using model reference adaptive control (MRAC) [23], [24], sliding mode or self tuning PIDs [16], [25]-[30]. The main advantages of FC compared to conventional one is that no exact mathematical model and also exact system parameters are needed. In [31]-[32], direct fuzzy model reference learning controller has been discussed. Also in [33]-[35], it has been proved that fuzzy controllers improve the tracking performances when rotor time constant affect the decoupling in FOC strategy. But in the other hand the software implementation presents limitation due to the high computational burden. As solution, fuzzy rules reduction and membership functions optimization were proposed in [36]. However, the performance investigations were limited to simulation results.

Conventional PI fixed parameters controller is less robust than a RST controller against disturbances. The RST polynomial controller can improve the system performances in terms of overshoot, rapidity, elimination of disturbance, and maintain a high level of performance. RST control is based on a synthesis of control law. It has been proved to be efficient and successful for a lot of industrial applications [37-39]. It is based on a polynomial, leading to transfer functions. The RST polynomials are calculated by the resolution of Bezout's equation [39].

In this paper, an adaptive fuzzy speed controller is used to adjust the PI gains. Then the RST speed controller is then used to be compared to the other developed speed controllers. Dspace 1104 digital signal processor fully programmable from the MATLAB/Simulink environment is used for the experimental implementation. Experimental tests are developed for step and ramp speed changes with speed inversion, which represents an extreme transient condition. Results are presented and discussed in each case. To confirm the robustness of each controller, parameter variation tests have been also applied.

2. THE PROPOSED IM DRIVE CONTROL SYSTEM

The proposed IM drive control system is based on an adaptive fuzzy speed controller to adjust the PI gains. The error, the change of error between the actual and the reference speed and saturation variable depending on the torque producing current are used as input. Fuzzy Takagi Sugeno controller type is used with singleton output values which have to adapt instantaneously the PI gains. Secondly, the RST speed controller synthesis with optimal pole placement relying on natural frequency and damping ratio of the system. Figure 1 shows the basic building block diagram of the proposed drive control system.

Where v_{sabc} and i_{sabc} are respectively the three-phase stator voltages and currents, (v_{sd}, v_{sq}) and (i_{sd}, i_{sq}) are respectively the stator voltages and currents in the synchronously rotating reference frame, ($\varphi_{rd}, \varphi_{rq}$) are the d and q axis components of rotor fluxes, ($v_{s\alpha}, v_{s\beta}$) and ($i_{s\alpha}$, $i_{s\beta}$) are respectively the stator voltages and currents in the stationary reference frame, Ω and $\omega_s$are respectively the mechanical rotor speed and the electrical synchronous speed (rad/s), θ_s is the rotor flux vector electrical position and $(.)^*$ denotes the reference value of the concerned variable.

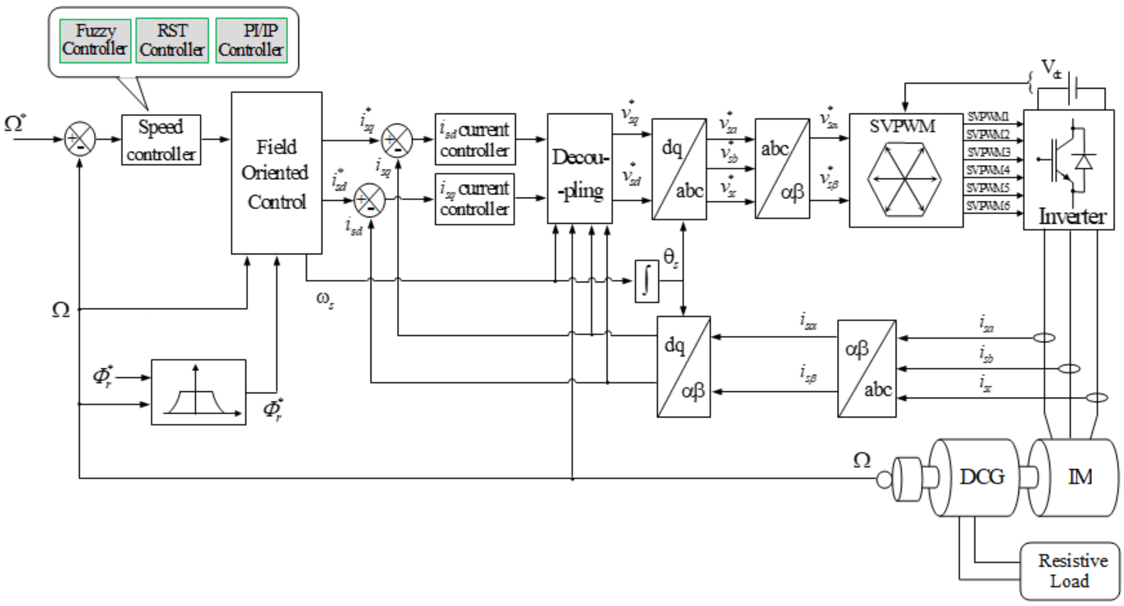

Figure 1. Basic drive system block diagram

Using stator currents and rotor fluxes as state variable, the IM model in synchronous reference frame can be represented by the following equation:

$$\begin{cases} \dfrac{di_{sd}}{dt} = \dfrac{-(R_s + (M_{sr}/L_r)^2 R_r)}{\sigma L_s} i_{sd} + \omega_s i_{sq} + \dfrac{M_{sr} R_r}{\sigma L_s L_r^2} \Phi_{rd} + \dfrac{M_{sr}}{\sigma L_s L_r} \omega \Phi_{rq} + \dfrac{1}{\sigma L_s} v_{sd} \\ \dfrac{di_{sq}}{dt} = \dfrac{-(R_s + (M_{sr}/L_r)^2 R_r)}{\sigma L_s} i_{sq} - \omega_s i_{sd} - \dfrac{M_{sr}}{\sigma L_s L_r} \omega \Phi_{rd} + \dfrac{M_{sr} R_r}{\sigma L_s L_r^2} \Phi_{rq} + \dfrac{1}{\sigma L_s} v_{sq} \\ \dfrac{d\Phi_{rd}}{dt} = \dfrac{M_{sr} R_r}{L_r} i_{sd} - \dfrac{R_r}{L_r} \Phi_{rd} + (\omega_s - \omega) \Phi_{rq} \\ \dfrac{d\Phi_{rq}}{dt} = \dfrac{M_{sr} R_r}{L_r} i_{sq} - \dfrac{R_r}{L_r} \Phi_{rq} - (\omega_s - \omega) \Phi_{rd} \\ \dfrac{d\Omega}{dt} = \dfrac{p\, M_{sr}}{L_r J} \left(i_{sq} \Phi_{rd} - i_{sd} \Phi_{rq} \right) - \dfrac{F}{J} \Omega - \dfrac{1}{J} T_L \end{cases} \tag{1}$$

Where R_s, R_r are respectively the stator and rotor winding resistance, L_s, L_r are respectively the stator and rotor inductance, M_{sr} is the mutual inductance, p is the number of pole pairs, $J$is the inertia moment, $F$is the viscous friction coefficient, T_e, T_L are respectively the electromagnetic and load torques $\sigma$is the total leakage factor, $T_r = \frac{L_r}{R_r}$ is the rotor time constant and ω is the electrical rotor speed (rad/s).

The vector control principle is to align the d axis of the (d, q) rotary reference frame with the rotor flux vector for the *IM*, so as to control separately the electromagnetic torque and the rotor flux. According to (1), the model of the motor can be expressed by the following equations:

$$\begin{cases} \dfrac{di_{sd}}{dt} = \dfrac{-(R_s + (M_{sr}/L_r)^2 R_r)}{\sigma L_s} i_{sd} + \omega_s i_{sq} + \dfrac{M_{sr} R_r}{\sigma L_s L_r^2} \Phi_r + \dfrac{1}{\sigma L_s} v_{sd} \\ \dfrac{di_{sq}}{dt} = \dfrac{-(R_s + (M_{sr}/L_r)^2 R_r)}{\sigma L_s} i_{sq} - \omega_s i_{sd} - \dfrac{M_{sr}}{\sigma L_s L_r} \omega \Phi_r + \dfrac{1}{\sigma L_s} v_{sq} \\ \dfrac{d\Phi_r}{dt} = \dfrac{M_{sr} R_r}{L_r} i_{sd} - \dfrac{R_r}{L_r} \Phi_r \\ 0 = \dfrac{M_{sr} R_r}{L_r} i_{sq} - (\omega_s - \omega) \Phi_r \\ \dfrac{d\Omega}{dt} = K.\, i_{sq} - \dfrac{F}{J} \Omega - \dfrac{1}{J} T_L \end{cases} \tag{2}$$

with $K = \frac{p\, M_{sr}}{L_r J} \Phi r$

Vector control of IM is used in direct field orientation, where sensors or models are used to calculate the position and the magnitude of the rotor flux or indirect method, where the speed position is used. The system contains two control loops in d and q axis as shown in Figure 1.

2.1. Current control in d axis

The voltage transfer function (TF) between v_{sd} voltage and i_{sd} current is given by:

$$\frac{i_{sd}}{v_{sd}} = \frac{1}{R_s + \sigma L_s s} \text{, where } s \text{, is the Laplace operator} \tag{3}$$

Using the compensation synthesis technique, the closed loop TF with PI controller is given by:

$$\frac{i_{sd}}{i_{sd}^*} = \frac{1}{1 + (\sigma L_s / K_{pd}) s} \tag{4}$$

Imposing the settling time t_r, the obtained dynamic is fixed by the following parameters:

$$K_{pd} = \frac{3 \cdot \sigma L_s}{t_r} \quad \textit{and} \quad K_{id} = K_{pd} \cdot \frac{R_s}{\sigma L_s} \tag{5}$$

2.2. Speed control

i_{sq} current is calculated in the same way of i_{sd} current. The speed internal block diagram is shown in Figure 2 for the IP structure, where as PI structure is illustrated in Figure 3. The closed TF of speed regulation with IP controller is given by the following equation:

$$\frac{\Omega}{\Omega^*} = \frac{K_i K_p K/J}{s^2+((F+K_pK)/J)s+K_iK_pK/J} \tag{6}$$

K_i and K_P parameters of IP speed controller are chosen in order to have the best dynamic performances. So as to fix the aimed overshoot and the settling time by imposing damping ratio ξ and natural frequency ω_n, (6) is used to calculate the K_i and K_p parameters to obtain the desired dynamics:

$$K_p = \frac{2\xi\omega_n J-F}{K} \quad \text{and} \quad K_i = \frac{J\omega_n^2}{K_pK} \tag{7}$$

The closed loop TF with PI controller is given by:

$$\frac{\Omega}{\Omega^*} = \frac{(K_p.K/J)\cdot(s+K_i/K_p)}{s^2+((F+K_pK)/J)s+K_iK_pK/J} \tag{8}$$

The K_i and K_P parameters in function of the damping ratio ξ and the natural frequency ω_n are given by:

$$K_p = \frac{2\xi\omega_n J-F}{K} \quad \text{and} \quad K_i = \frac{J\omega_n^2}{K} \tag{9}$$

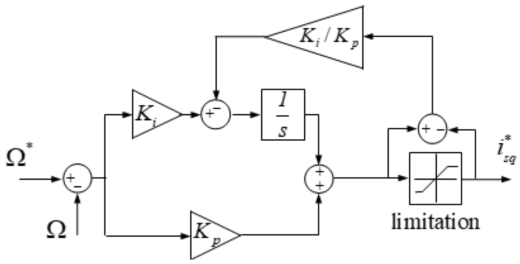

Figure 2. IP Internal structure block diagram

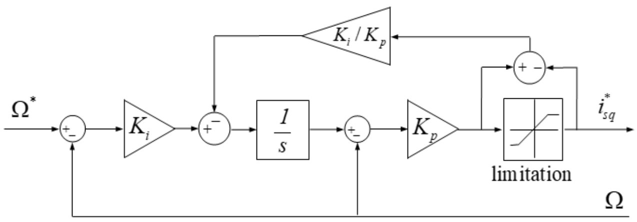

Figure 3. PI Internal structure block diagram

3. ADVANCED SPEED CONTROLLERS

3.1. RST speed controller

To impose a strong dynamic for the torque control, a RST polynomial regulator is used to control the speed. At the opposite of the conventional PI controller with only one degree of freedom, the RST controller is considered as a regulator with two degrees of freedom. It consists of a multi-objective control that easily leads to optimization of the dynamic response time and the disturbance rejection. The basic structure of the RST controller is given by Figure 4, where $A(s)/B(s)$ represents the open loop TF system.

$$u(s) = \frac{T(s)}{S(s)}r(s) - \frac{R(s)}{S(s)}y(s) \tag{10}$$

The input control signal is given by a special filtering of the output and the reference. The synthesis of the RST controller is done so that to impose a desired closed-loop TF:

$$y(s) = \frac{B_d(s)}{A_d(s)}r(s) \tag{11}$$

Let the closed loop transfer function of the block diagram of Figure 4 be:

$$G_{BF}^d(s) = \frac{y(s)}{r(s)} = \frac{B(s).T(s)}{A(s).S(s)+B(s).R(s)} \tag{12}$$

This transfer function must be equal to the desired closed loop function so that:

$$\frac{B(s).T(s)}{A(s).S(s)+B(s).R(s)} = \frac{B_d(s)}{A_d(s)} \tag{13}$$

The following equations have to be resolved:

$$A(s)\ S(s) + B(s)\ R(s) = A_d(s) \quad \text{and} \quad B(s)\ T(s) = B_d(s) \tag{14}$$

The following transformation is applied:

$$\begin{aligned} &A(s)\ S(s) + B(s)\ R(s) = B(s)\ A_d(s) \\ &T(s) = B_d(s) \end{aligned} \tag{15}$$

To determine$R(s)$ and $S(s)$, it is necessary to solve the BEZOUT equation:

$$A(s)\ \ S(s) + B(s)\ \ R(s) = B(s)\ A_d(s) \tag{16}$$

The placement synthesis adjustment of the RST controller is to synthesize three polynomials R, S and T on the basis of a robust pole placement. The mechanical part TF can be given by:

$$G(s) = \frac{\Omega}{i_{sq}^*} \approx \frac{K}{J.s+F} \tag{17}$$

The association of the RST structure with the system allows to impose a global dynamic of second order. The desired transfer function is:

$$G_{BF}^d(s) = \frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2} \tag{18}$$

The polynomials S, R and T are as following:

$$S(s) = s_0 + s_1 s, \quad R(s) = r_0 + r_1 s, \quad T(s) = t_0 \tag{19}$$

The polynomials coefficients of the *RST* can be calculated using the Bezout equation. Thus, we obtain:

$$s_0 = 1, \quad s_1 = \frac{K}{J}, \quad r_0 = \omega_n^2, \quad r_1 = 2\zeta\omega_n - \frac{s_0 J}{K}, \quad T(s) = t_0 = \omega_n^2 \tag{20}$$

3.2. Fuzzy speed controller

Fuzzy logic controllers are able to incorporate experience, intuition and heuristics into the system and do not rely on mathematical models. However, they have high computational burden during hardware and software implementation, especially when the number of fuzzy logic inputs and the dimension of the rule base are important [32].

Fuzzy control techniques have been explored and used by several researchers. It has gained great attention in the area of electromechanical devices. This is due to its potential to improve the speed regulation of the drive system. Because of its ability to incorporate the human intuition in design process and linguistic rules with an '*if-then'* structure [6].

The proposed adaptive fuzzy controller (AFC) showed in Figure 5 is based on Sugeno method thanks to its computational efficiency and it is well suited for linear technique, such as *PI* conventional controllers. The main difference between *Mamdani* and *Sugeno* is that the *Sugeno* output membership functions are either linear or constant. Inputs are the error between the actual and the reference speed, its first derivative and the V_{sat} variable due to the saturation of i_{sq} as shown in Figure 6. Their expressions are thus underneath:

$$\begin{cases} E_r(t) = \Omega^*(t) - \Omega(t) \\ dE_r(t) = E_r(t) - E_r(t-1) \{ \\ V_{sat} = I_{sqmax}^{*\overset{*}{s}q} \end{cases} \tag{21}$$

Output is the weight to be used in order to adapt the ***PI*** controller by adjusting in real time proportional and integral action using the center of gravity method as follows:

$$W = \frac{\sum_{i=1}^n c_i . \mu_i}{\sum_{i=1}^n \mu_i} \tag{22}$$

Scale factors gains defined as GEr, GdEr, Gsat, GW_Integ and GW_Prop are used to make the AFC sensitive and near to the normalized defined input and output range values. Input variables fuzzy set are Negative: N. Positive: P. Zero: Z. The values range of output variables are: Zero: Z. Positive normal: PN. Positive Big: PB.

The following heuristic considerations have been noted from the observation of the process behavior: Integral action: Overshoot is mainly caused by integral term. Significant reduction causes system response to exceed the set point, Proportional action: Increasing proportional term reduces the leading time but increases the oscillations, Saturation: A variable depending on isq current is introduced for limitations due to the saturation. Table 1 gives the rules used for this AFC. The use of triangular membership functions for the inputs and singleton in output is advantageous for time calculation asn shown in Figure 6 and Figure 7. The AFC speed surface is presented in Figure 8.

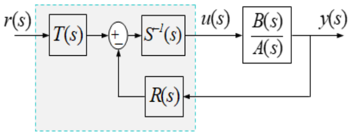

Figure 4. RST controller block diagram

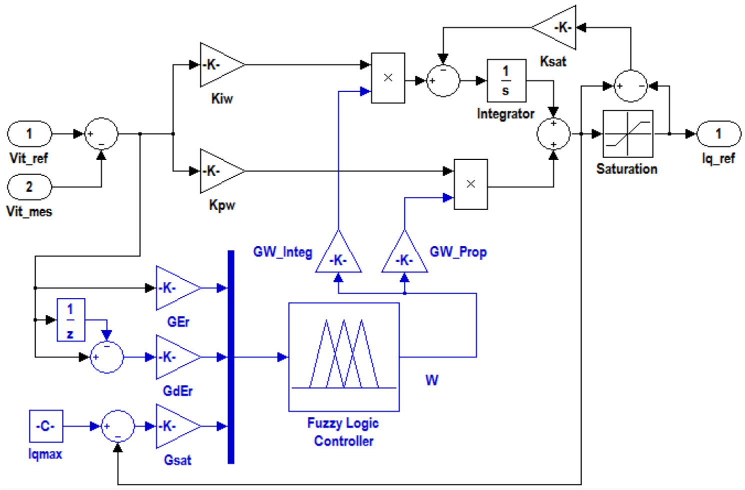

Figure 5. AFC Internal structure block diagram

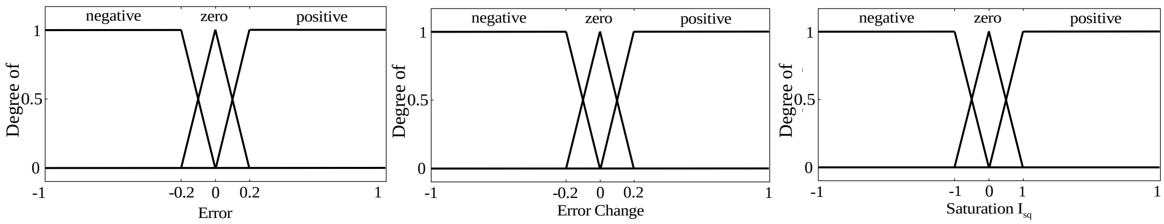

Figure 6. Input membership functions of the *AFC*

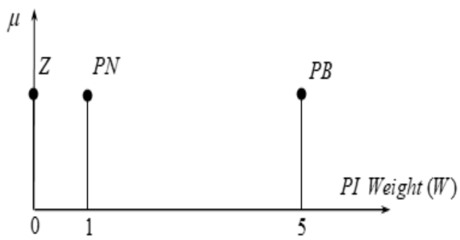

Figure 7. Output membership functions of the AFC

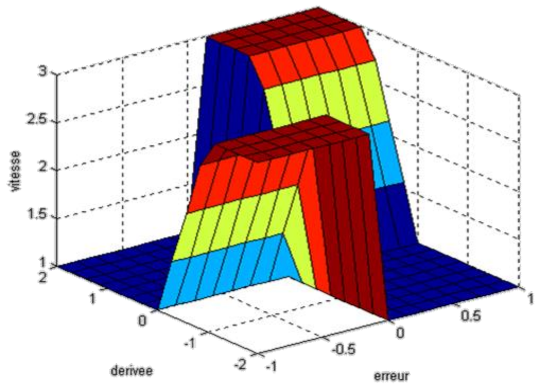

Figure 8. Speed AFC surface

Table 1. A FC rules

Inputs			Output *W*
E_r	dE_r	V_{sat}	
N	/	*N*	***Z***
N	/	*P*	***PB***
P	/	*N*	***PB***
P	/	*P*	***Z***
Z	/	/	***PN***
/	/	*Z*	***PN***
/	*Z*	/	***PN***
N	*N*	*Z*	***PB***

4. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental test bench developed in LIAS laboratory is composed by DS1104 board, squirrel cage IM (LEROYSOMER LS 90), DC generator supplying a resistor used as a dynamic load, three-phase IGBT inverter allowing the realization of different power supply modes, current measurement module, speed sensors and PC with Matlab/Simulink and control-desk program. Figure 9 shows the experimental test bench and Figure 10 presents its different parts. The controller is built through Simulink block diagram. The MATLAB real time workshop routine produces C-code from Simulink block diagram. 10 KHz space vector Modulation (SVM) algorithm was used to drive the three-phase inverter. The interface between Simulink and the dSPACE1104 allows the control algorithms to be run on the hardware. With control-desk, it is possible to change controller parameters and reference signals while an experiment is running. To reduce the time calculation, Simulink lookup table models were used to realize the fuzzy rules.

Different test cases were completed in the laboratory under different operating conditions in order to evaluate the performances of the proposed *AFC* and *RST* controllers. Two benchmarks were proposed. The first one is for step reference in order to evaluate the dynamic performances of each developed speed controller. The second one is for speed ramp inversion benchmark at nominal conditions and it is used to study the system behaviors in terms of trajectory tracking.

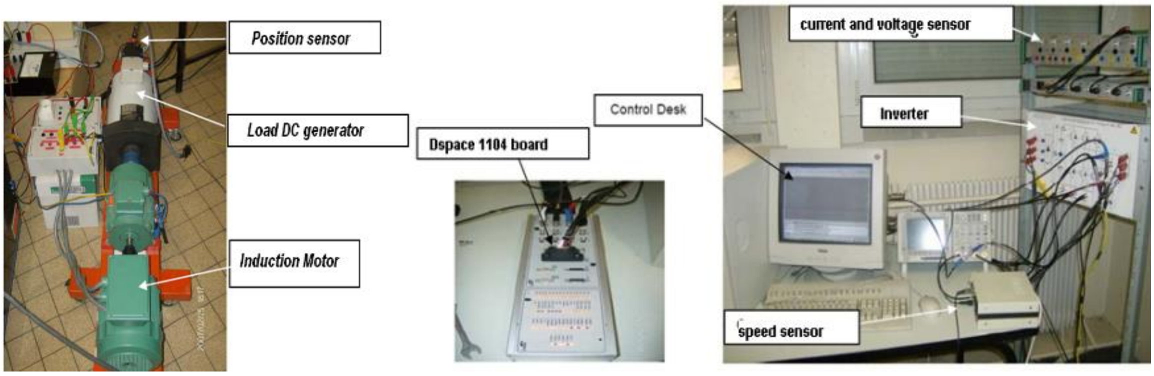

Figure 9. Experimental test benches

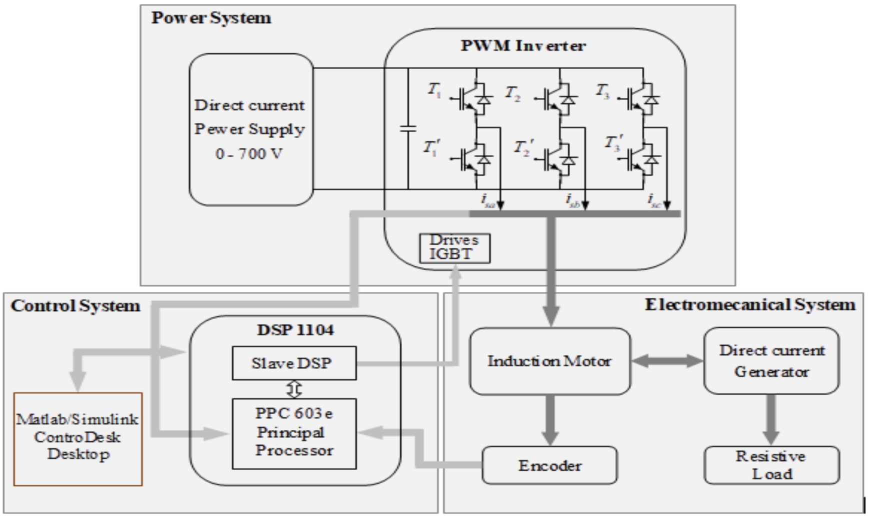

Figure 10. Experimental test bench schemes

The closed-loop control system would be stable and would meet tracking performance (rise time, overshoot, and settling time) at transient, regulation performance (load disturbance rejection) at steady state. For the step tracking trajectory, the speed is imposed between +500 and -500 rpm. The nominal load disturbance torque was applied and removed for the positive and negative speed reference. The experimental results are presented in Figure 11, Figure 12 and Figure 13.

The ramp benchmark at nominal conditions imposes a speed inversion between +1400 and -1400rpm. The results are also illustrated in Figure 14, Figure 15 and Figure 16. The tracking performance is obtained including steady state, speed inversion and load disturbance rejection. Several experimental tests were realized for different gains values.

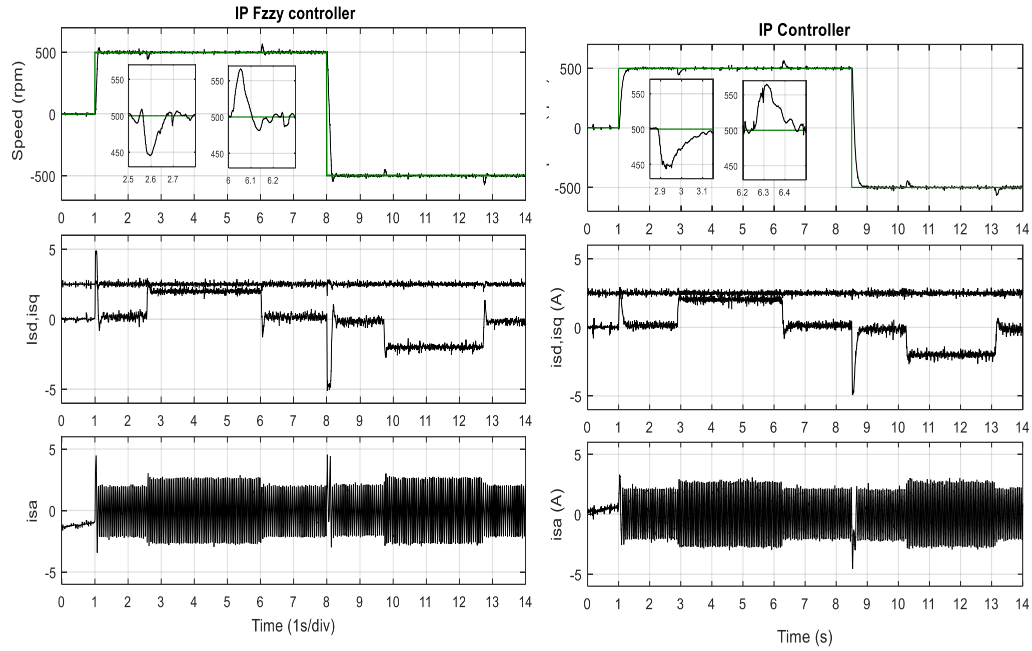

Figure 11. Performances of conventional IP and AFC-IP controllers in case of step benchmark

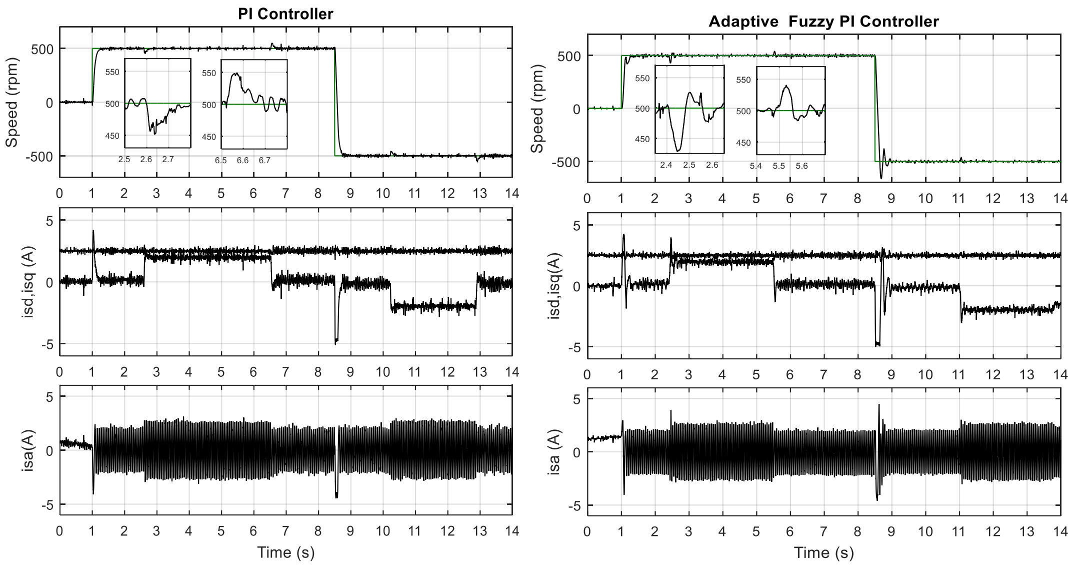

Figure 12. Performances of conventional PI and AFC-PI controllers for step benchmark

The best gains PI and IP speed controllers successfully implemented are given in Table 2. In the same way, the chosen AFC scale factors gains are given in Table 3, whereas the Table 4 contains the RST polynomials coefficients. It can clearly be seen that AFC and RST speed controllers have faster tracking characteristics than PI and IP conventional speed controllers. The RST provides best-induced error reduction for load disturbance rejection. The obtained dynamic performances (rise time, settling time, overshoot) are shown in Table 5.

To confirm the robustness of the proposed AFC and RST speed controllers against conventional used controllers, different experimental parameters variation tests were developed for each controller. For the rotor resistance, the variation was done between 70% and 150%. The inertia moment J variation was done between 70% and 130% for conventional and AFC controllers. The results are presented in Figure 17 and Figure 18. With the RST speed controller, the variation was done until 50% for the rotor resistance and until 170% for the inertia moment. Obtained results are also shown in Figure 19. Best results were provided with AFC and

RST speed controllers, which confirms the robustness against parameters variation. In particular, dynamic performances of RST speed controller were conserved. The used IM parameters are also given in Table 6.

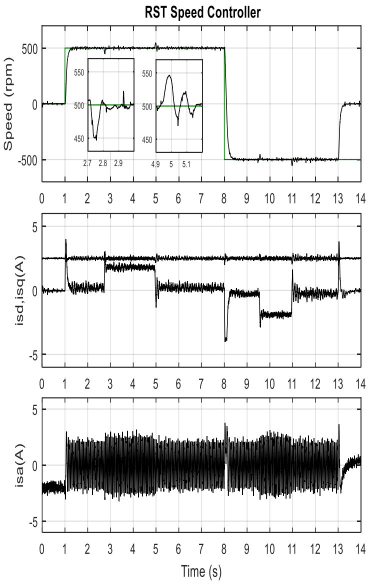

Figure 13. Performances of RST controller for step benchmark

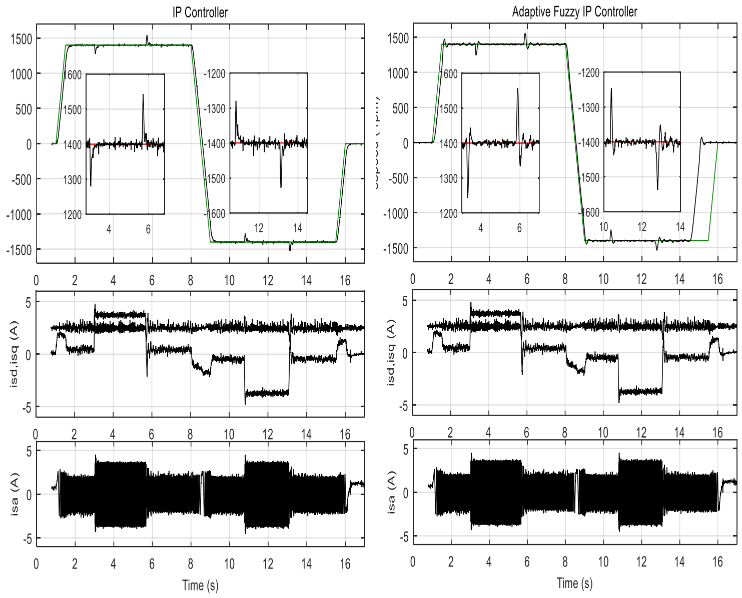

Figure 14. Performances of conventional IP and AFC-IP controllers in case of ramp benchmark

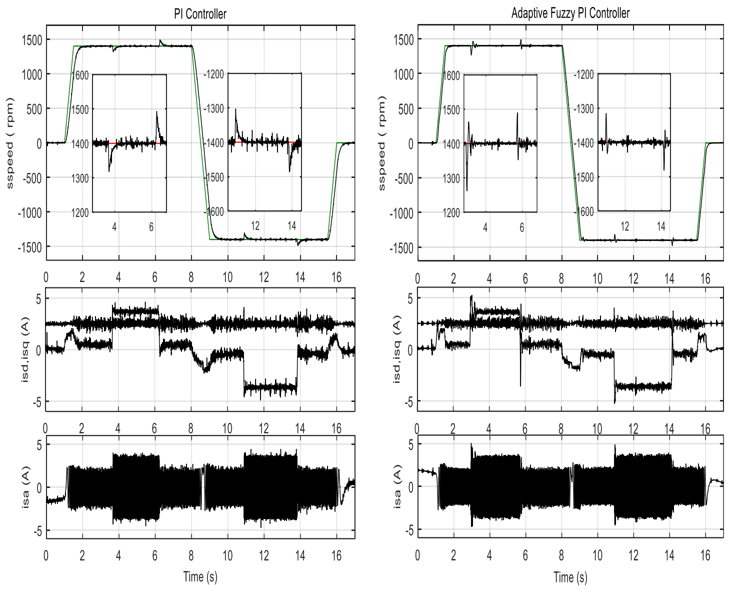

Figure 15. Performances of conventional PI and AFC-PI controllers for ramp benchmark

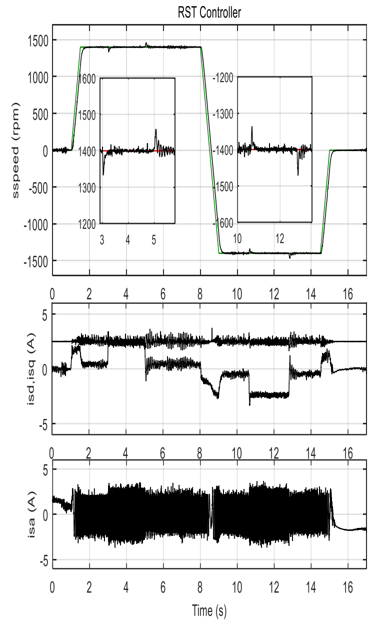

Figure 16. Performances of RST controller for ramp benchmark

Table 2. IP and PI parameters

	IP	PI
K_p	0.1350	0.0870
K_i	10.2300	0.5872

Table 3 AFC scale factors gains

Gains	Values
G_{Er}	0.009
G_{dEr}	0.7
G_{w_integ}	2
G_{w_Prop}	0.3

Table 4. RST coefficients

Coefficients	Values
s_0	1
s_1	117.7158
r_0	625
r_1	35.3415
t_0	625

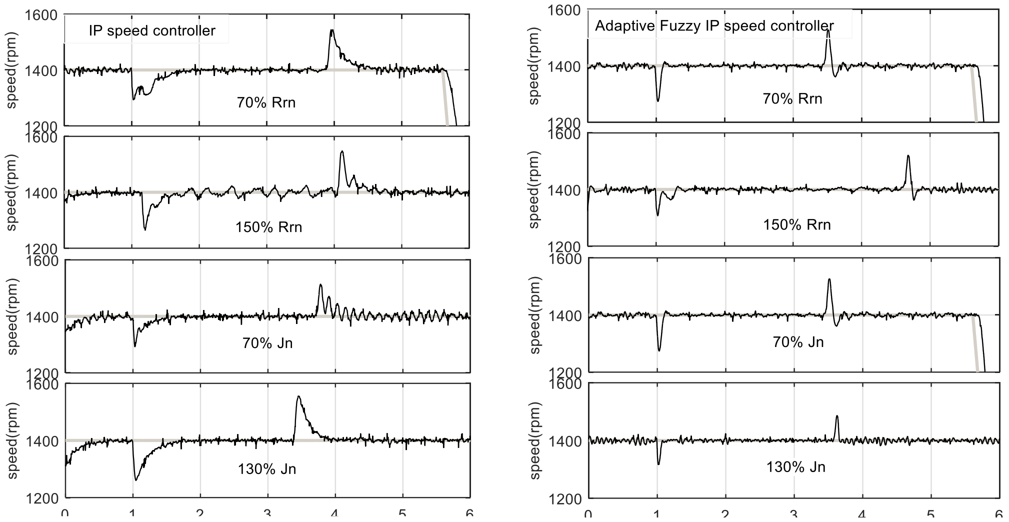

Figure 17. Robustness tests of conventional IP and AFC-IP controllers

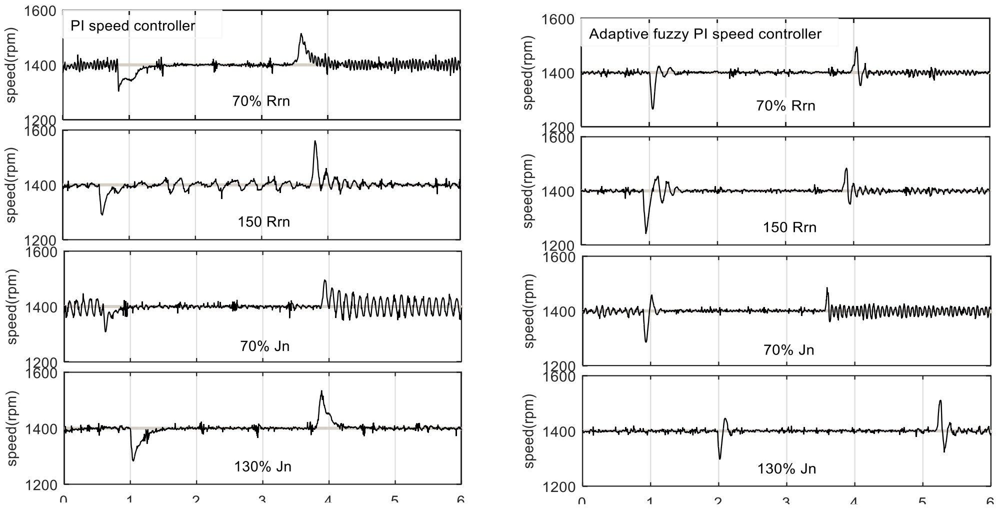

Figure 18. Robustness tests of the conventional PI and AFC-PI controllers

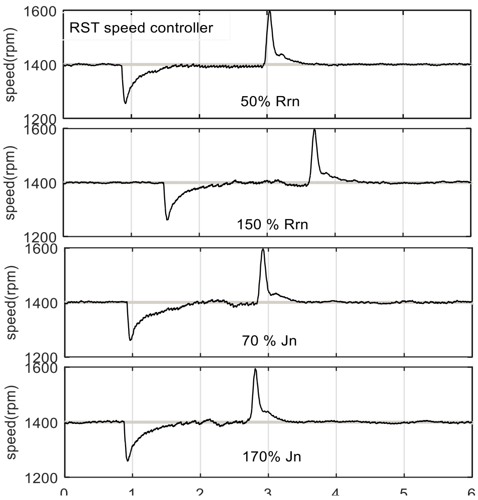

Figure 19. Robustness tests of conventional RST controller

Table 5. Experimental results of controller's dynamic performances

Speed controllers	Rise time (s)	Settling time (s)	Overshoot (%)
IP	0.1430	0.2070	0
AFC-IP	0.0580	0.0780	7
PI	0.1110	0.1600	0
AFC-PI	0.0710	0.1140	0
RST	0.0510	0.1400	0

Table 6. IM parameters

Type		Squirrel Cage Induction Motor
Rated Power		1.1 Kw
Rated Frequency		50 Hz
Number of Poles	$2p$	4
Mutual inductance	M_{sr}	0.4475 H
Stator inductance	L_s	471.8 mH
Rotor inductance	L_r	471.8 mH
Stator resistance	R_s	9.6500 Ω
Rotor resistance	R_r	4.3047 Ω
Inertia Moment	J	29.310^{-3} Kg.m^2
Friction Coefficient	F	$13.0\ 10^{-3}$ Nm/rad.s^{-1}

5. CONCLUSION

This work reports successful development and implementation of RST and AFC speed controller to improve the indirect FOC of IM drive system. Experimental obtained results show that both PI and IP structures give good response when the AFC provides better closed-loop tracking performances under external disturbances, such as load changes and speed inversion. The use of linear and constant membership functions makes the AFC implementation simple and advantageous in terms of calculation time. However, the RST speed controller accelerates the response time without overshoot thanks to proper poles placement. All tests show that AFC and RST speed controllers provide fast and robust speed settlings compared to the PI/IP conventional controllers. Robustness tests confirm their efficiency. In perspective, the proposed RST and AFC speed controllers can be combined with a new configuration using the fuzzy adaptation mechanism to act on the calculation of the RST polynomial parameters.

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