

REAL TIME IMPLEMENTATION OF NONLINEAR PI CONTROLLER FOR THE INDUCTION MACHINE CONTROL

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ABSTRACT

In this paper a nonlinear PI (NPI) controller are proposed and compared with the conventional linear fixed-gain PI controller to improve the overall performance of the system by incorporating a sector-bounded nonlinear gain in cascade with a conventional PI control architecture. The proposed controller has implemented for a 1.5-kW three-Phase Induction Motor are completely carried out using a dSPACE DS1104 digital signal processor (DSP) based real-time data acquisition control (DAC) system, and MATLAB/Simulink environment. Digital experimental results are presented to show the improvement in performance of the proposed algorithm.

Keywords: PI controller; Nonlinear PI controller; Induction Machine; IFOC; dSPACE.

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1. INTRODUCTION

Due to important progress in power electronics and micro-computing, the control of the ac electric machines has known considerable developments that lead to the possibility of high performance real time implantation applications. The induction machine (IM), known for its



robustness, cost, reliability, and effectiveness is the subject of several researches [1]. However, it has traditionally been used in industrial applications that do not require high-performances, because of its highly non-linear behavior and coupled structure. On the other hand, separately excited dc machines were largely used for variable speed applications since they produce torque and flux that are naturally decoupled and that can be controlled independently. Since Blaske and Hasse have developed the technique known as vector control [2,3], the use of the induction machine has become more and more frequent. This control strategy can provide the same performance as achieved from a separately excited dc machine, and it is proven to be well adapted to all types of electrical drives associated with induction machines [4].

The most widely used controllers in industrial applications are PID-type controllers because of their simple structure and good performances in a wide range of operating conditions [5]. In fixed gain controllers, these parameters are selected by methods such as the Ziegler and Nichols, pole placement, etc. PID controllers have been utilized for control of diverse dynamical systems ranged from industrial process to aircraft and ship dynamics [1–4]. Although linear fixed-gain PID controllers are often adequate for controlling a nominal physical process, the requirements for high-performance control with changes in operating conditions or environmental parameters are often beyond the capabilities of simple PID controllers [12].

In this paper, we propose and evaluate a nonlinear PI (NPI) controller for speed control of the IM. While, the improvement of NPI controller is achieved by the use of nonlinear gains [10], the combination of nonlinear terms can provide additional degrees of freedom to achieve a much improved system performance. The NPI controller can adjust its gains in real time according to the speed error and it is able to reject the effect of time-varying and nonlinear behaviors in the process [11]. To demonstrate the effectiveness of the proposed control scheme, we apply the proposed scheme to the speed control of a three-phase induction motor using a dSPACE DS1104 digital signal processor (DSP) based real-time data acquisition control (DAC) system, and MATLAB/Simulink environment.

This paper is organized as follows: In section II, we present model of the used induction motor (IM) and the indirect field-oriented control of the IM, the synthesis of the nonlinear PI

controller is outlined in section III. Experimental results and performance of the controllers are compared in section IV. Finally, some remarking conclusions are summarized in section V.

2. INDIRECT FIELD-ORIENTED CONTROL OF THE THE INDUCTION MOTOR

The machine considered in this paper, is a three-phase squirrel-cage asynchronous machine. The dynamic model of the Δ -connected induction motor can be expressed in the d-q synchronously rotating frame as [1, 4]:

$$\left\{ \begin{aligned} \frac{di_{sd}}{dt} &= -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma \tau_r}\right) i_{sd} + \omega_e \cdot i_{sq} + \frac{L_m}{\sigma L_s L_r \tau_r} \phi_{rd} + \frac{L_m \omega_r}{\sigma L_s L_r \tau_r} \cdot \phi_{rq} + \frac{1}{\sigma L_s} V_{sd} \\ \frac{di_{sq}}{dt} &= -\omega_e \cdot i_{sd} - \left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma \tau_r}\right) i_{sq} - \frac{L_m \omega_r}{\sigma L_s L_r \tau_r} \cdot \phi_{rd} + \frac{L_m}{\sigma L_s L_r \tau_r} \phi_{rq} + \frac{1}{\sigma L_s} V_{sq} \\ \frac{d\phi_{rd}}{dt} &= \frac{L_m}{\tau_r} i_{sd} - \frac{1}{\tau_r} \phi_{rd} + (\omega_e - \omega_r) \phi_{rq} \\ \frac{d\phi_{rq}}{dt} &= \frac{L_m}{\tau_r} i_{sq} - \frac{1}{\tau_r} \phi_{rq} + (\omega_e - \omega_r) \phi_{rd} \\ \frac{d\omega_r}{dt} &= \frac{3 P^2 L_m}{2 J L_r} (i_{sq} \cdot \phi_{rd} - i_{sd} \cdot \phi_{rq}) - \frac{f_c}{J} \cdot \omega_r - \frac{P}{J} T_1 \end{aligned} \right. \quad (1)$$

where σ is the coefficient of dispersion and is given by

$$\sigma = 1 - \frac{L_m^2}{L_r \cdot L_s} \quad (2)$$

L_s , L_r and L_m : the stator, rotor, and mutual inductances,

R_s and R_r : the stator and rotor resistances,

ω_e and ω_r : the electrical and rotor angular frequency,

ω_{sl} : the slip frequency ($\omega_e - \omega_r$),

τ_r : the rotor time constant (L_r/R_r),

P : the number of pole pairs.

The main objective of the vector control of induction motors is, to control independently the flux and he torque as DC machines, this is done by using a d-q rotating reference frame synchronously with the rotor flux space vector [4]. In ideally field-oriented control, the rotor

flux linkage axis is forced to align with the d-axes, and it follows that [1, 6]:

$$\phi_{rq} = \frac{d\phi_{rq}}{dt} = 0 \quad (3)$$

$$\phi_{rd} = \phi_r \quad (4)$$

Considering (3) and (4), the torque equation becomes analogous to that of the dc machine and can be described as:

$$T_e = \frac{P \cdot L_m}{L_r} \phi_{rd} \cdot i_{sq} \quad (5)$$

The decoupling control method with compensation is to obtain the inverter output voltages such that [6]:

$$V_{sd}^* = \left(K_p + K_i \frac{1}{s} \right) (i_{sd}^* - i_{sd}) - \omega_e \sigma L_s i_{sq}^* \quad (6)$$

$$V_{sq}^* = \left(K_p + K_i \frac{1}{s} \right) (i_{sq}^* - i_{sq}) + \omega_e \sigma L_s i_{sd}^* + \omega_e \frac{L_m}{L_r} \phi_{rd} \quad (7)$$

By using, the placement poles method the proportional and integral gains of the PI speed controller (K_p and K_i) are determined by [6,13]:

$$K_p = \frac{2 \cdot \rho \cdot J - f_c}{P} \quad (8)$$

$$K_i = \frac{2 \cdot J \cdot \rho^2}{P} \quad (9)$$

Where the desired poles are: $s_{1,2} = \rho(-1 \pm j)$, the value of ρ is given in appendix.

3. SPEED CONTROL OF THE IM BY THE NONLINEAR PI (NPI)

In order to improve the control quality, a nonlinear PI (NPI) IM speed controller can be constructed as shown in fig.2. The combination of nonlinear terms can provide additional degrees of freedom to achieve a much improved system performance. The nonlinear PI controller action is given by [9]

$$T_e^* = K_p \cdot fal(e, \alpha_p, \delta_p) + K_i \cdot fal(\int e, \alpha_i, \delta_i) \quad (10)$$

$$fal(x, \alpha, \delta) = \begin{cases} |x|^\alpha \text{sign}(x) & |x| > \delta, \delta > 0 \\ \frac{x}{\delta^{1-\alpha}} & |x| \leq \delta \end{cases} \quad (11)$$

Where

$fal(x, \alpha, \delta)$ is a nonlinear function represented in fig.1,

x is a variable which can be e or $\int e \cdot dt$,

e is the error between the speed reference and real speed of the IM ($e = \omega_r^* - \omega_r$).

K_p and K_i are respectively proportional and integral gains of the PI controller, presented in (8) and (9),

T_e^* is the referential torque (the control signal),

The parameters α_p and α_i are constant, empirically chosen in the range 0 to 1. When

$\alpha_p = \alpha_i = 1$, the controller becomes a linear PI controller,

δ is a constant, which can be set empirically to a small value.

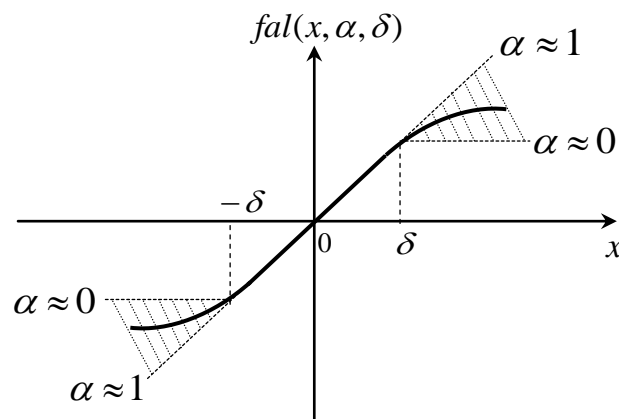


Fig.1. The nonlinear function

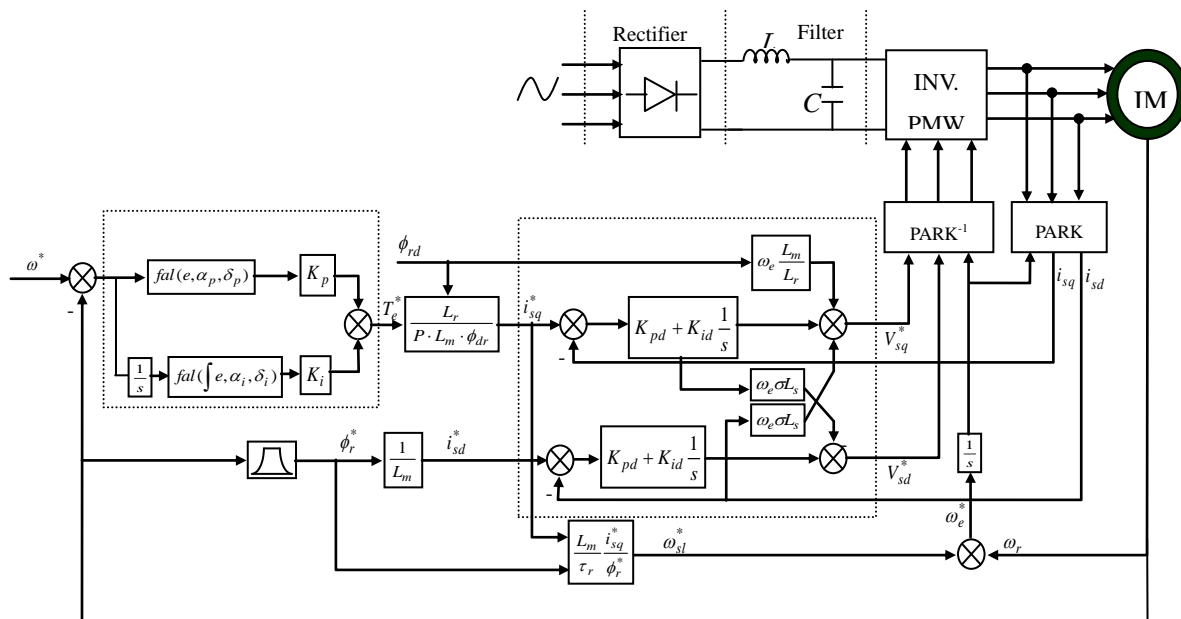


Fig.2. Block diagram of IM control by a nonlinear PI controller.

4. EXPERIMENTAL RESULTS

The configuration of the overall control system is shown in fig. 2. It consists of an induction motor, a ramp comparison current-controlled pulse width modulated (PWM) inverter, a slip angular speed estimator, and an inner indirect field oriented controller and an outer speed feedback control loop with the nonlinear PI controller.

The fig.3 shows the photo of the experimental banc test which consist of the following elements:

- (1). Three-phase cage induction motor with the following characteristics: Δ connected, four poles, 1.5 kW, 1426 min⁻¹, 230/400 V, 50 Hz with the 1024 points integrated incremental coder.
- (2). Three-phase rectifier,
- (3). Electrical insulation and adaptation card and current sensor LEM LA25-NP for measuring stator currents (realized in the laboratory),
- (4). Brushless rotary torque sensor,
- (5). Powder brake,
- (6). Measuring device for mechanical quantities,
- (7). Measuring device for electrical quantities,

- (8). Load mechanical torque simulator,
- (9). Three-phase power supply,
- (10). Relay card for automatic brake control with dSPACE,
- (11). The dSPACE DS1104 with ControlDesk GUI software for release 6.2.

The experimental results are provided to further demonstrate the effectiveness of the proposed control system. The nonlinear PI controller, indirect field-oriented control, and the current regulation are all executed in Intel(R) Core(TM) i3 CPU 540@3.07 GHz, 3Go RAM via Matlab/Simulink software with Real-Time Workshop to deliver the PWM signals to the drive circuit. The sampling time is 2×10^{-4} sec.

In the experimental part, by using the relay card (10) and the Simulink programming, we specified the times of the application of the load via the powder brake as well the change of the speed reference of the IM. Fig. 4 shows the experimental response to disturbance of the continuous time implementation of the nonlinear PI controller when the machine is stepped up to 1426 min⁻¹ under no load and load torque disturbance equal to 4.3 N·m is suddenly applied at 10 sec and eliminated at 20 sec. As shown in the fig.4(a), the comparison in the experimental part, between the nonlinear PI controller and the PI controller demonstrates that the NPI controller rejects the load disturbance more rapidly than the PI controller with a negligible steady state error.

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In the fig. 5, we present the experimental response to disturbance of the continuous time implementation of the NPI controller when the machine is stepped up to 1426 min⁻¹ under no load, followed by a set point inversion (-1426 min⁻¹) at 30 sec. The fig. 5(a) shows that the response of the system with the NPI controller follows its reference perfectly with a minimum of the overshoot and the rising time better than the PI controller.

For these different operating regimes, defluxing is maintained with the NPI controller.

Furthermore, compared with the experimental results of the linear PI control system, the responses are much improved using the nonlinear PI controller.

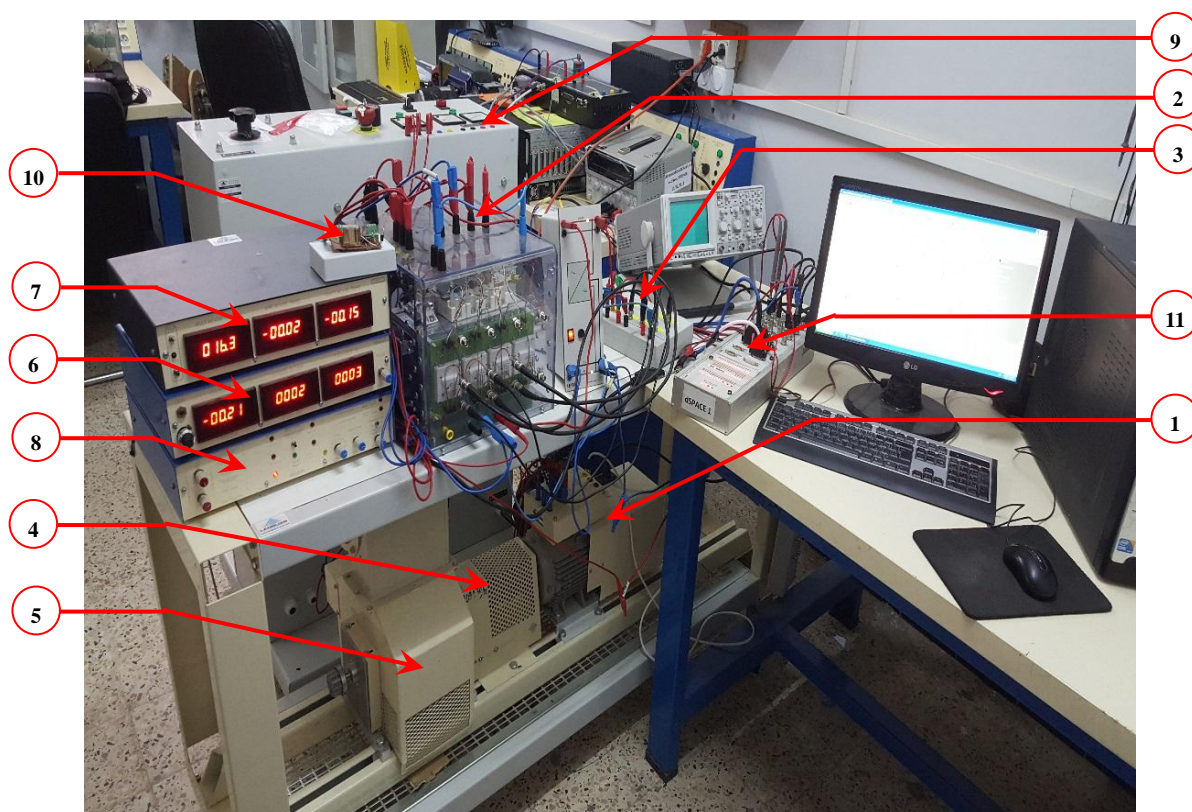
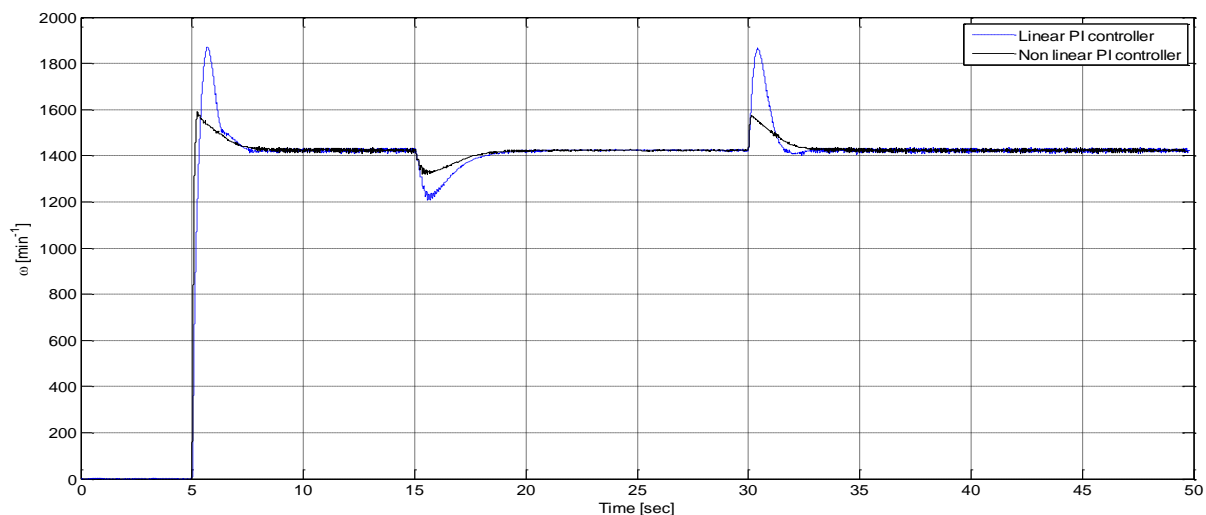
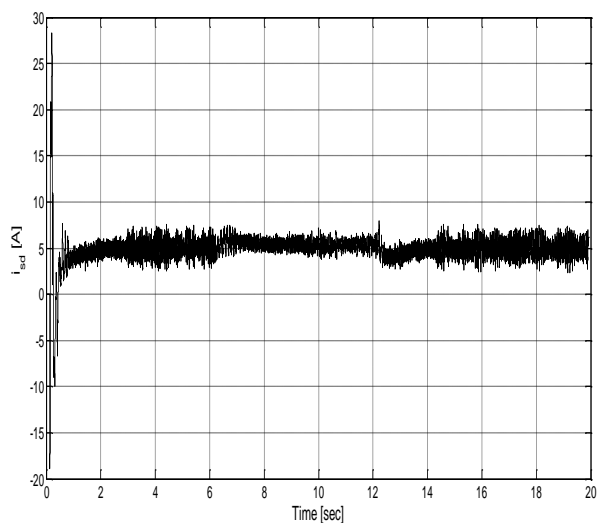


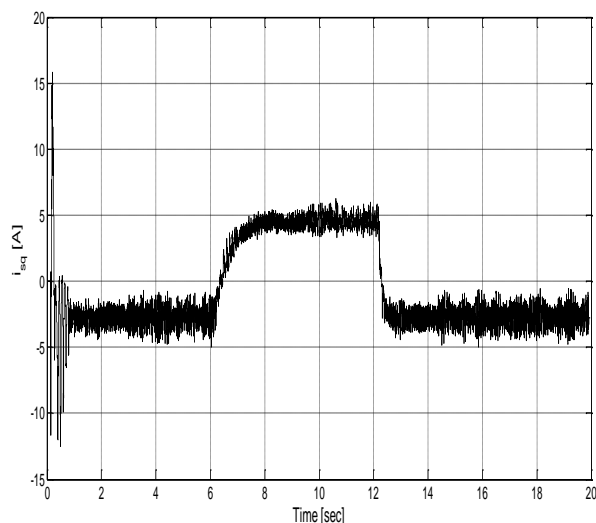
Fig.3. Photo of the experimental banc test



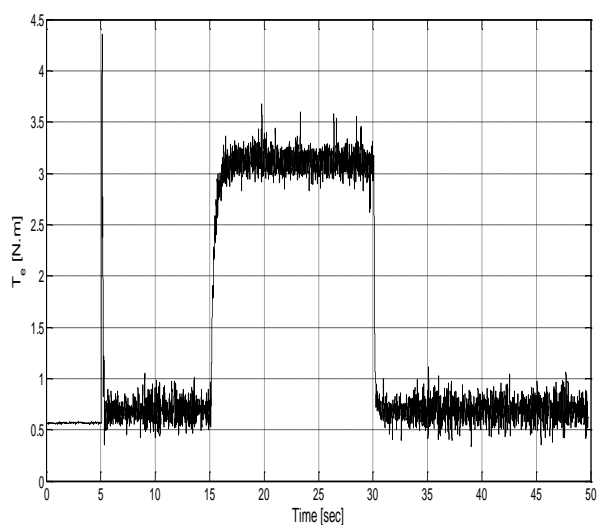
(a) Rotor speed [min^{-1}]



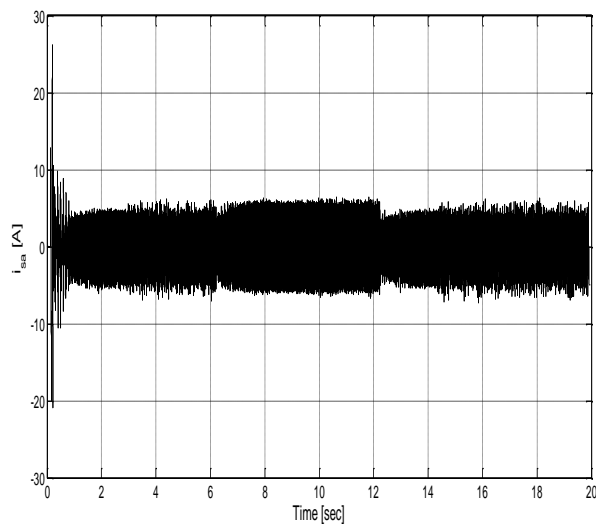
(b) Current i_{sd} [A]



(c) Current i_{sq} [A]

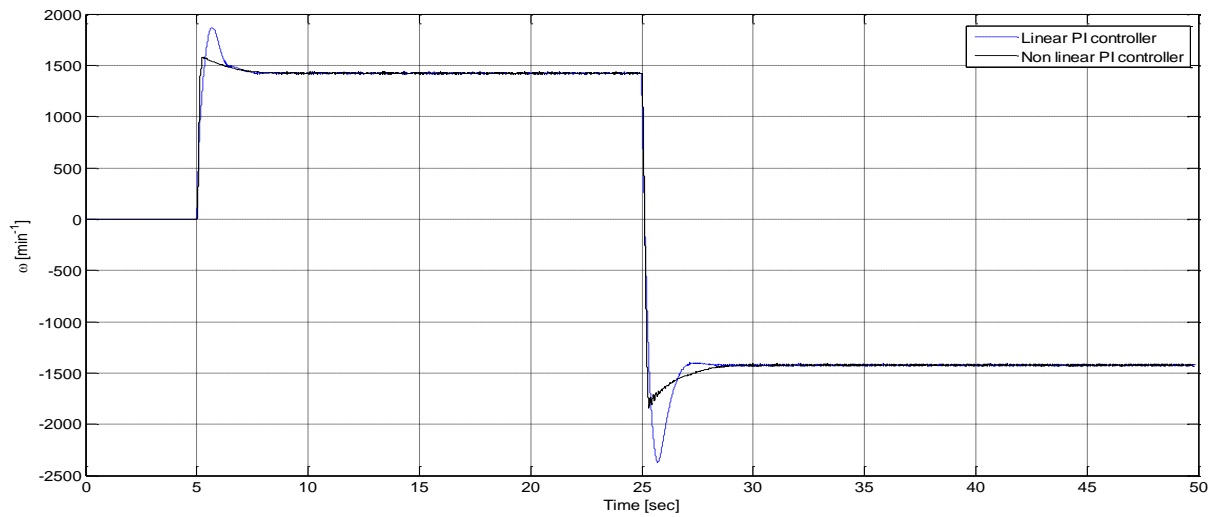


(d) Mechanic torque [N.m]

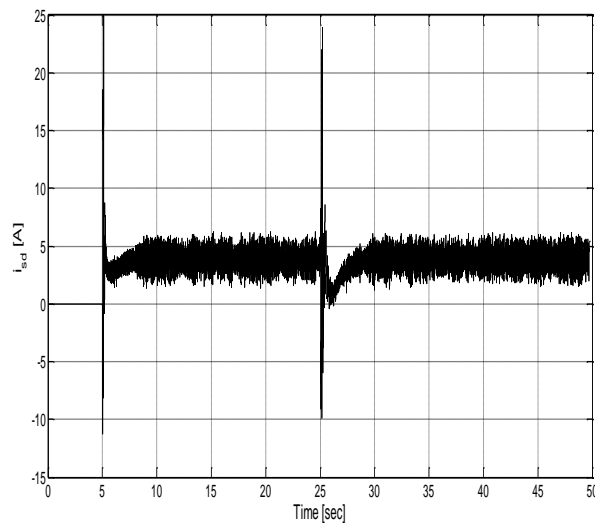


(e) Current i_{sa} [A]

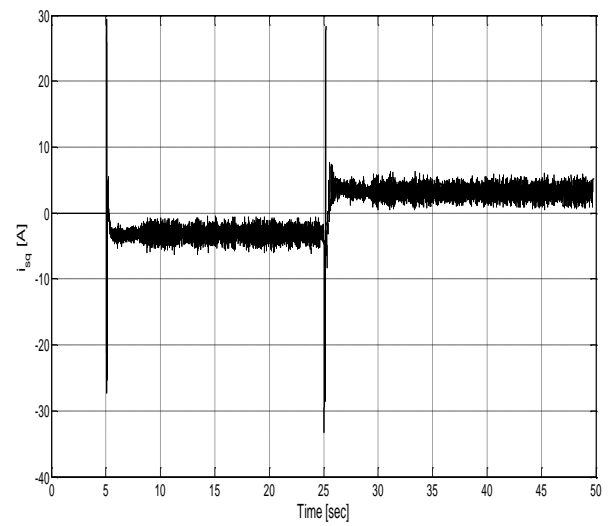
Fig.4. Experimental results of the control of the IM by the nonlinear PI controller under load variation



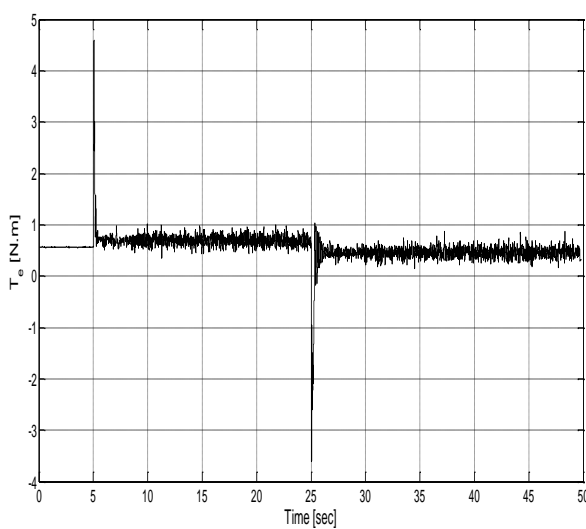
(a) Rotor speed [min^{-1}]



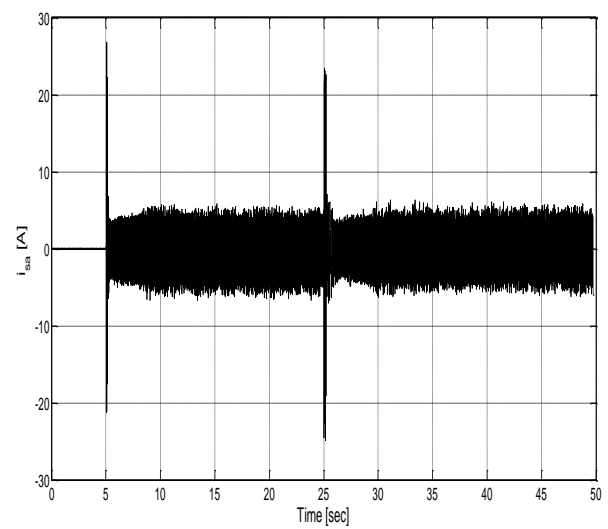
(b) Current i_{sd} [A]



(c) Current i_{sq} [A]



(d) Mechanic torque [N.m]



(e) Current i_{sa} [A]

Fig.5. Experimental results of the control of the IM by the nonlinear PI controller under reference variation

5. CONCLUSION

In this paper, we proposed a nonlinear PI controller based speed control of the IM. In the proposed control method, the combination of nonlinear terms has provide additional degrees of freedom to achieve a much improved system performance under reference variations and load torque variations. The proposed scheme has presented satisfactory performances (no overshoot, minimal rise time, best disturbance rejection) for different operating regimes of the IM. Experimental results show that the performance and disturbance rejection with nonlinear PI controller is significantly improved as compared to a system with standard PI controllers.

APPENDIX: INDUCTION MOTOR PARAMETERS

P_n [kW]	1.5	R_s [Ω]	4.37	J [kg/m ²]	0.0653
V_n [V]	230	R_r [Ω]	3.79	f_c [N·m·s/rad]	0.0092
$\cos \varphi$	0.82	L_s [H]	0.745	P	2
ω_n [min ⁻¹]	1426	L_r [H]	0.53	ϕ_r [Wb]	1.8150
f [Hz]	50	L_m [H]	1.93	ρ	1.2

6. REFERENCES

- [1] Bose B.K., "Modern Power Electronics and AC Drives," Prentice Hall, 2002.
- [2] I.Takahashi, T.Noguchi, "A new quick response and high efficiency control strategy of an induction motor," IEEE Transaction Industrial Application, vol. IA-22, pp. 820 – 827, Sept./Oct. 1986.
- [3] M. Depenbroak, "Direct Self-Control (DSC) of Inverter-Fed Induction Machine" IEEE Trans. Power Electronics, Vol. 3, No. 4, pp. 420 –429, Oct. 1988.
- [4] Baghli, L.: Contribution to induction machine control: using fuzzy logic. Neural Networks and Genetic Algorithms, Doctoral Thesis, Henri Poincare University, January 1999.
- [5] Peter Vas: Sensorless Vector and Direct Torque Control, Oxford University Press, London, 1998, ch.1.

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- [6] H. Le-Huy, "Comparision of field-oriented control and direct torque control for induction motor drives", intenational Conference Rec. IEEE Industry Applications Soc. Annual Meeting, 1999, pp. 1245 – 1252.
- [7] R. Arulmozhiyal and K. Baskaran, "Implementation of a Fuzzy PI Controller for Speed Control of Induction Motors Using FPGA," Journal of Power Electronics, vol. 10, pp. 65-71, 2010.
- [8] Z. Yin Hai, et al., "A Novel SVPWM Modulation Scheme," in Applied Power Electronics Conference and Exposition, 2009. APEC 2009. Twenty-Fourth Annual IEEE, 2009, pp. 128-131.
- [9] F. Mokhtari, P. Sicard and A. Hazzab, 'Cascade Decentralized Nonlinear PI Control Continuous Production Process' , ELECTRIMACS, Québec, Canada, Jun. 2008, CD-ROM.
- [10] Cruz, M. A. Gallegos, R. Alvarez, and F. Pazos, "Comparison of several nonlinear controllers for induction motors," IEEE Int'l. Power Electronics Congress (CIEP), 2004, pp. 134 –139.
- [11] Y.X. Su, Dong Sun, B.Y. Duan, 'Design of an Enhanced Nonlinear PID Controller, Mechatronics 15 (2005) pp. 1005–1024
- [12] Gunawan Dewantoro, 'Multi-objective Optimization Scheme for PID-Controlled DC Motor', International Journal of Power Electronics and Drive System (IJPEDS), Vol. 7, No. 3, September 2016, pp. 734-742
- [13] Medjdoub khessam, Abdeldejbar Hazzab, Bouchiba Bousmaha, M Bendjima, 'Fuzzy Adaptive PI Controller for DTFC in Electric Vehicle', International Journal of Power Electronics and Drive System (IJPEDS), Vol. 4, No. 4, December 2013

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