FUZZY AND PI POSITION CONTROL WITH SLIP GAIN TUNING IN INDUCTION SERVO DRIVES – A COMPARATIVE ANALYSIS

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***Abstract* – Vector control of induction motors (IM) is a technique that revolutionized the electric drive technology, for enabling the induction motor to become a competitor to direct current (DC) motors for servo drive applications. Some inherent limitations of classical controllers, however, lead to the choice of emerging control techniques that exhibit better performance in the presence of nonlinearities, as well as greater robustness against parameter variations, typically present in induction motors. Fuzzy controllers are employed here, in place of the more common proportional-integral (PI) controllers, for a position control system. The performance of fuzzy controller is shown to be more robust than that of the PI controller, under rated condition as well as several other load conditions. On the same line, a second fuzzy controller utilizes the rotor flux error to adapt the slip gain, required to properly generate the unit vectors in an indirect vector control system, drastically reducing the coupling effect between IM rotor flux and torque responses, usually caused by rotor resistance variations. By utilizing the IM *d-q* model and sinusoidal PWM inverter model, the entire proposed control system is realistically simulated with SIMULINK software to demonstrate its effectiveness. An experimental platform was constructed; utilizing a TMS320F240 DSP evaluation board from Texas Instruments Inc. to verify the dynamic performance of the system, with good results.**

KEYWORDS

Induction motors, fuzzy control, classical control, slip gain tuning.

I. INTRODUCTION

The indirect vector control is the most popular technique used in high performance induction motor (IM) drives, particularly for position control, due to its capability to operate at zero speed. In this technique, the rotor flux position is obtained in a feed-forward manner from the information of a mechanical variable (position or speed) and the slip frequency reference ω_{sl}^* [1]. The latter is obtained from the torque component of the stator current reference (i_{qs}^*), as indicated in Eq. *1*, where K_s is the slip gain, defined in Eq. 2. K_s is basically dependant on the correct knowledge of rotor time constant τ_r.

$$\omega_{sl}^* = K_s i_{qs}^* \tag{1}$$

$$K_s = \frac{R_r}{L_r}\frac{L_m}{\psi_r^*} = \frac{1}{\tau_r i_{ds}^*} \tag{2}$$

With correct computation of K_s, the IM indirect vector controlled system dynamics exhibits decoupling between torque and flux responses, and a linear, DC machine like system is obtained. In fact, vector control linearizes the complex IM model, and reduces its order. In that case, classic control strategies (such as PID controllers) present good performance. However, under variable load conditions, these strategies may fail (resulting in poor dynamic responses), mainly for position control.

Another common problem with indirect vector control is the influence of the machine parameters on the slip computation from Eqs.(1) and (2). For instance, R_r may vary with the temperature causing incorrect slip estimation. In this case the torque has a higher order profile, and under or over excitation occurs in the presence of a load torque [5,8]. The normalized equation that relates rotor flux, slip gain, and load torque, in steady state conditions, with negligible magnetic saturation is given by:

$$\frac{\psi_r}{\psi_r^*} = \sqrt{\frac{1+\left(\frac{i_{qs}}{i_{ds}}\right)^2}{1+\left(\frac{\hat{K}_s}{K_{so}}\frac{i_{qs}}{i_{ds}}\right)^2}} \tag{3}$$

The impact of a poor estimate of slip gain is show in Fig. 1, derived from Eq. 3, with normalized flux “versus” slip gain, for various load conditions, where K_{so} is the correct slip gain value.

Nowadays, fuzzy logic based algorithms are widely used to perform control actions. They can deal with non-linearities and parameters variations and also provide more flexibility and robustness than classical control strategies [4,7]. In a fuzzy controller, the control surface can be modified by adding “ad-hoc” knowledge to the “if-then” rule base controller, or change model granularity, fuzzyfication, inference, or defuzzyfication procedure [2]. In this paper fuzzy controllers are proposed to improve the system dynamic response under parameter variations in a certain range, and also to provide proper slip gain tuning. This is made to ensure correct computation of the unit vectors for an indirect vector controlled IM position control system.

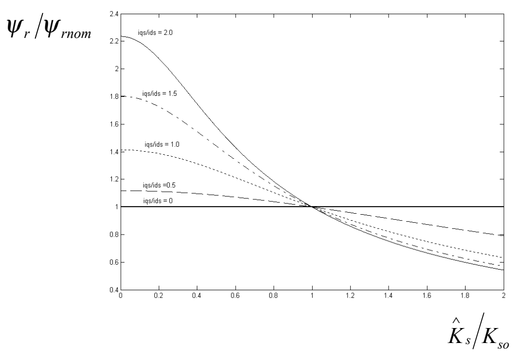


Fig. 1 - Impact of slip gain detuning on normalized rotor flux.

II. SYSTEM DESCRIPTION

Fig. 2 presents a simplified block diagram of the proposed fuzzy controlled system, used for simulation studies. A second system (not shown), employing PI controllers, was also constructed, and tuned by frequency domain methods, for a specified phase margin, under nominal conditions, and its performance was investigated, initially through simulation, for comparison purposes.

The inertial load represented by a steel bar imposes both a disturbance in load torque (a function of angular position), and an increase in the mechanical time constant. The flux estimate is obtained from an open loop observer, based on the inverse gamma model of the induction motor, as indicated by Eq. (4) [3]. It requires the acquisition of the stator voltage, in addition to the already available stator currents, but it is not dependant on the rotor resistance.

$$\psi^{s}_{qdr} = \frac{L_r}{L_m}\int (v^{s}_{qds} - R_s i^{s}_{qds})dt - \frac{\sigma}{1-\sigma} L_m i^{s}_{qds} \tag{4}$$

In practice, low pass filters are utilized in place of the pure integrator of Eq. (4), to prevent saturation of the integrator due to drifts and offsets from the sensors, as well as to overcome initial condition problems that plague pure integrators. To improve the quality of the observer at low frequencies, a feed forward scheme is employed, that utilizes the reference flux in the stationary reference frame D^s-Q^s [6]. The rule base for the position and speed controllers were constructed intuitively, employing the meta rules generally used in fuzzy controllers [9], as well as the expected behavior of the system. In Fig.3 the fuzzy sets and rule base for each controller are shown. The rule base for the slip gain tuning controller was constructed from the characteristics of the indirect vector control system when $K_s < K_{so}$ (overflux) e $K_s > K_{so}$ (underflux). In fig. 3, fig. 4, and fig. 5, *n* stands for negative, *p* for positive, *zr* for zero, *m* for medium, *b* for big. The parameters of the induction motor appear in Table 1.

III. RESULTS

The system was modeled and validated initially through simulation using SIMULINK software. Figure 6 shows the frequency response for both Fuzzy and PI controllers, where it can be seen that the system bandwidth with fuzzy controllers is larger than that with PI controllers.

Figure 7 shows the responses to a position step of 2π for both PI and Fuzzy controllers, for rated inertia as well as five times the rated value. At no load, the responses are quite similar, but with increased inertia, the PI response exhibits overshoot, an undesirable feature for a position controller, whereas the response of the Fuzzy controller remains fast, and is properly damped. It is clear that the Fuzzy controller is more robust against parameter variations than the PI controller.

The adaptation mechanism was tested, and the results are shown in Fig. 8. In Fig. 8a, a sudden increase in R_r is imposed to the system. The normalized slip gain K_s converges rapidly, demonstrating that the tuning will be effective in real condition, where no sudden changes occur. Another situation is depicted in Fig. 8b, where K_s is initialized with twice the correct value. Once more, proper convergence is obtained, as well as in Fig. 8c, where K_s was initialized with half of the correct value.

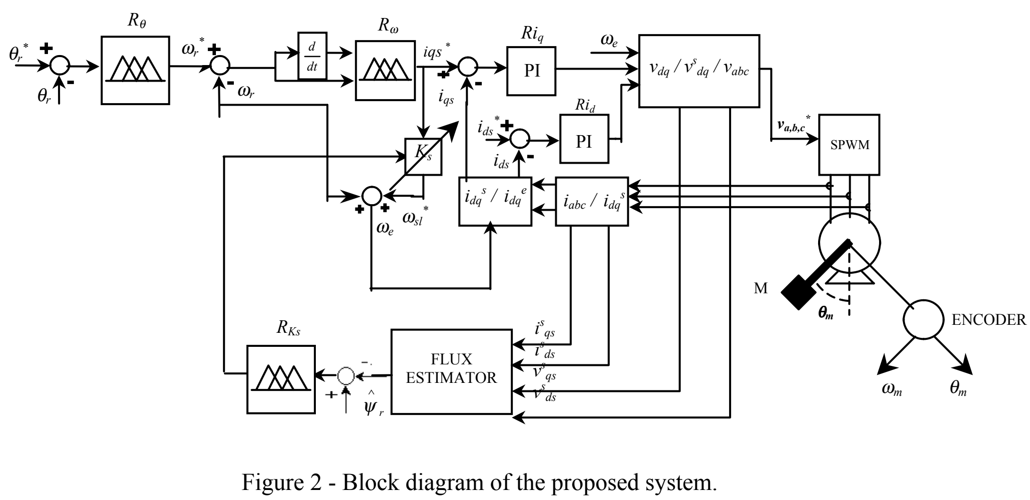
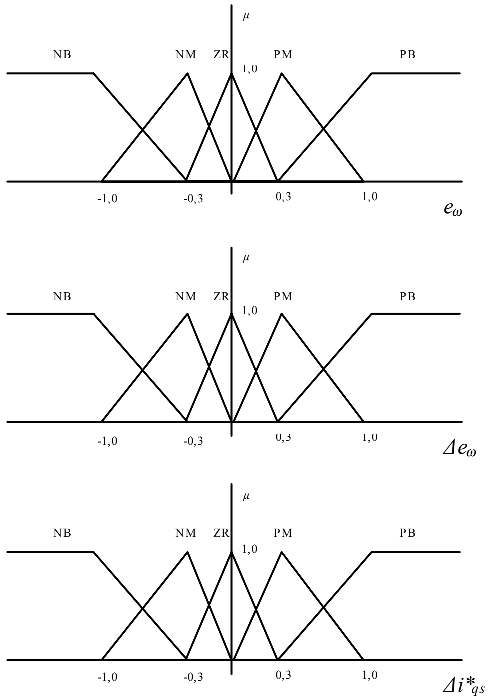
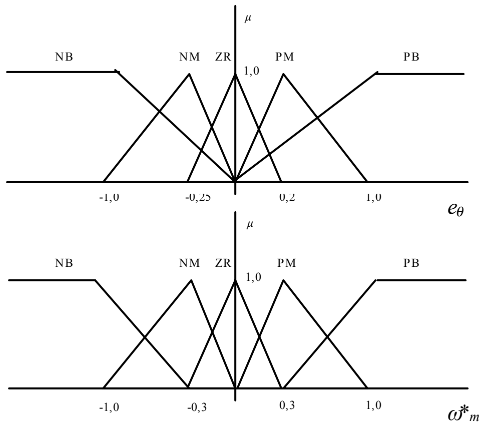


Figure 2 - Block diagram of the proposed system.



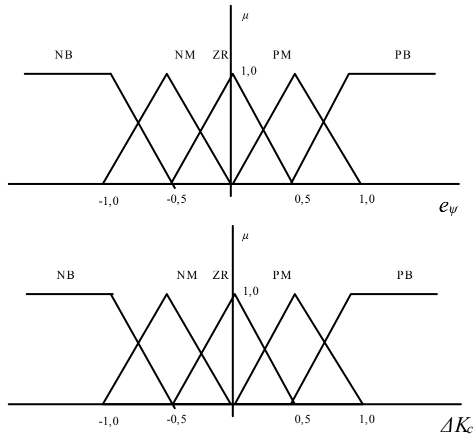
e_ω / Δe_ω	NB	NM	ZR	PM	PB
NB	NB	NB	NM	NM	ZR
NM	NB	NM	NM	ZR	ZR
ZR	NM	NM	ZR	PM	PM
PM	ZR	ZR	PM	PM	PB
PB	ZR	PM	PM	PB	PB

Fig. 3 - Fuzzy sets and rule base for the speed loop fuzzy controller.



e_ω	NB	NM	ZR	PM	PB
ω_r^*	NB	NM	ZR	PM	PB

Fig. 4 - Fuzzy sets and rule base for the position loop fuzzy controller.



e_ψ	NB	NM	ZR	PM	PB
ΔK_c	PB	PM	ZR	NM	NB

Fig. 5 - Fuzzy sets and rule base for the slip gain tuning fuzzy controller.

Experimental results were obtained from DSP-based hardware platform (TMS320F240, Texas Instruments) to assess the system dynamic performance The modulation technical used in this case was SVPWM (space vector PWM), with 5 kHz switching frequency. The systems was tested at no-load, and with a load with five times the rated inertia, as well as a nonlinear position dependant torque disturbance. The system responses for one revolution step are shown in Figure 9. Under no-load conditions, the fuzzy controllers exhibit a faster response than that of the PI controllers. Introducing the load leads to the deterioration in both responses. However, the response of the fuzzy controllers again is better, despite the oscillations and the settling time, with no overshoot. Through a finer tuning in the fuzzy rules, it is possible to improve the performance of the fuzzy controllers, but a significant amount of time can be dispensed in this process.

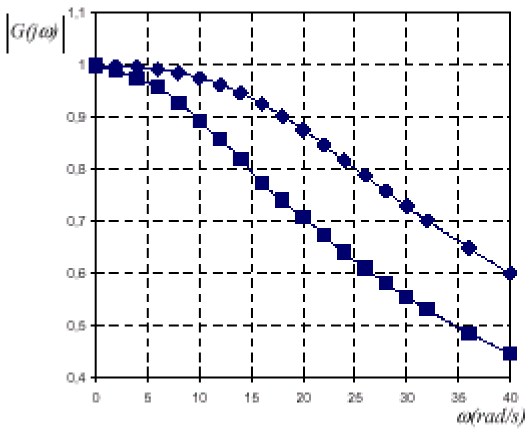
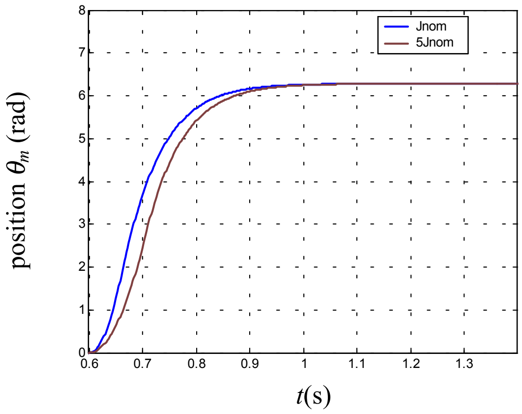
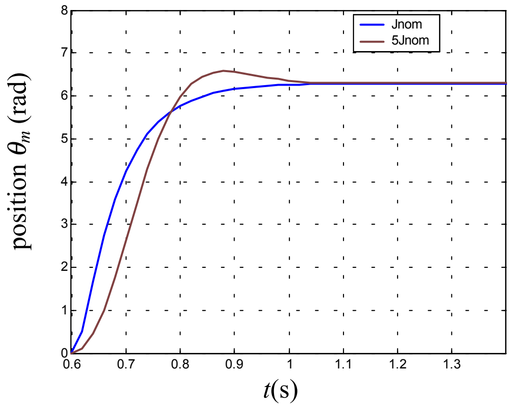


Fig. 6 - Simulated bandwidth for both Fuzzy (upper curve) and PI controllers (lower curve).



(i)



(ii)

Fig. 7 Simulation responses to a step input with rated inertia and 5 times the rated intertia. (i) With fuzzy controllers (ii) With PI controllers.

IV. CONCLUSIONS

This paper demonstrates the improvement in the dynamics of an induction motor servo drive system due to the utilization of fuzzy logic-based controllers in place of the classical PI strategies. Both simulation and experimental studies were conducted, with good results. Only the DSP implementation of the slip gain tuning faced some difficulties, since the rotor flux estimation is hard to implement in a fixed-point processor, due to the large time constants representation. Applications of the proposed system range from robotics and machine tools, to elevators and cranes.

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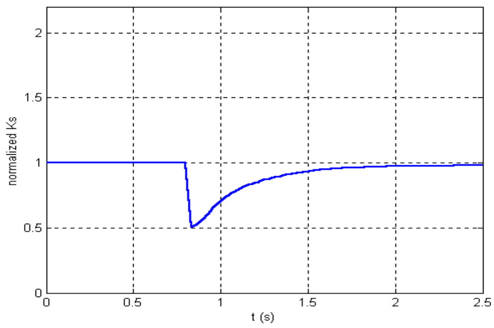
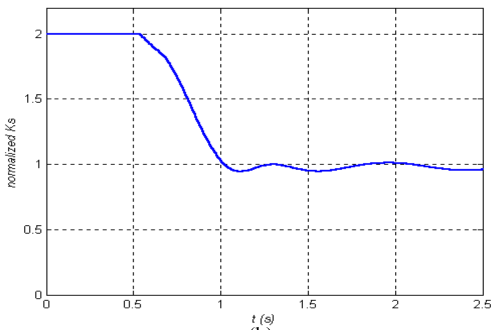
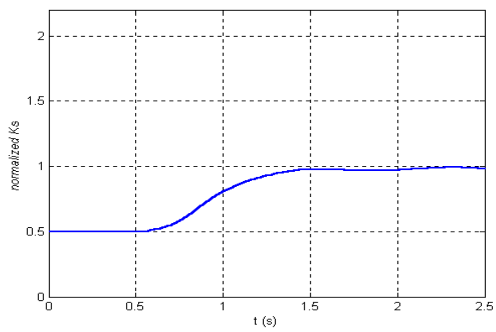


(a)

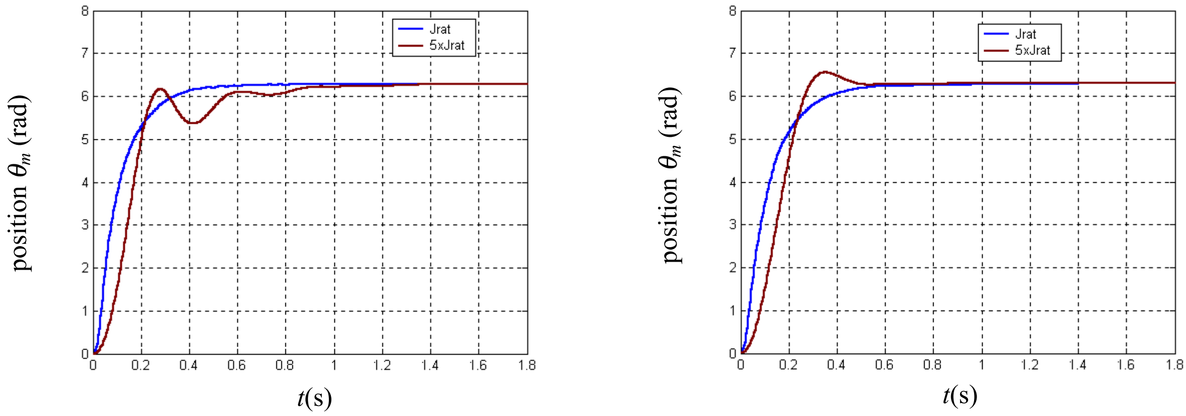


(b)



(c)

Fig. 8: Slip gain tuning for: (a)Sudden change in rotor resistance. (b,c)Incorrect initialization of K_s.



(i) *(i)*

Fig. 9 - Experimental responses to a step input with rated inertia and 5 times the rated intertia.
(i) With fuzzy controllers (ii) With PI controllers.

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Tab. 1 – Induction motor parameters and rated values.

Parameter / rated value	Magnitude	Unit
L_m	0.3506	H
L_s	0.3817	H
L_r	0.3817	H
R_s	13.4842	Ω
R_r	8.3566	Ω
J	0.00056	$kg.m^2$
B	0.0005	N.m.s
P_{rat}	0.18	kW
V_{rat}	220 / 380	V
f_{rat}	60	Hz
Pole number	4	-