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A NEW CONTROL ALGORITHM FOR ACTUATORS WITH AC MOTORS

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Abstract. Performance improvement and cost reduction achieved by microprocessors and power electronics in recent years have enabled the use of induction motors driven by frequency inverters. There is a competitive costs compared to brushed DC motors and also, with much higher reliability and energy efficiency. In this work it is investigated a position control law for a commercial induction AC motor with gear and drive powered by an inexpensive frequency inverter. This proposed control law is simple, efficient to real time implementation and does not depend on prior knowledge of the system's dynamic model. Experimental results, including unbalanced inertia coupled to the actuator's output shaft, showed good robustness in the rejection of external disturbances during reference position tracking. This control method has important practical aspects and can be very useful for engineers who need to control the angular position of AC motors.

Keywords: *Control, AC motor, position tracking, robustness, nonlinear friction.*

1. INTRODUCTION

In the automation industry, the position control for an electric actuator can be achieved through the use of either a stepper-motor, a DC motor, or a brushless DC motor (permanent magnet rotor) or an AC motor (induction type rotor). The first one is the most expensive, but requires the least amount of electronics for position control. The last one is the cheapest, but the most difficult to control. Recent improvements in power electronics and microprocessors have enabled an increased use of the inexpensive induction type AC motors (squirrel cage rotor). These motors are an efficient and cost competitive alternative to other types of drive setups. The main difficulty of controlling an induction type AC motor is the slippage of the rotor, regarding to the rotating magnetic field produced at the stator. Due to the large commercial interest and scientific challenges involved, several works have been focused on dynamic modeling of the motor and on the design of control laws. Baskya and Gobia (1999) proposed an AC rotation speed control of pumps and fans in heating, ventilating and air conditioning or in flow applications. Shen and Dai (2011) have proposed a method that positive or negative rotation speed of the motor is controlled directly by the positive and negative torque to improve the efficiency of the motor control. Shimada *et. al.* (2006) describe a position open loop control technique on AC servo motor using mechanical springs. Youb and Craciunescu (2007) presented a study about comparisons of various strategies for direct torque control of induction motors. Chitra and Prabhakar (2006) proposed fuzzy logic controller using field oriented control technique to motor torque control and showed simulations results. Aspalli *et. al.* (2012) present a design and an analysis of a three phase induction motor drive with volts hertz control (V/F) in closed loop using a PIC (Programmable Interface Controller). Teske *et. al.* (2003) proposed a rotor position estimate technique for an AC motor to achieve accurate position control. Cheon *et. al.* (2004), Bounadja *et. al.* (2010) and Sencer and Shamoto (2013) used sliding mode technique to achieve accurate position control of an AC servo motor. Mishra and

Choudhary (2012) proposed a comparative performance of PI and Neuro-Fuzzy control techniques to obtain a high performance speed control. Adaptive neuro-fuzzzy technique was proposed by Rashidi (2004) for controlling the rotor speed of an AC servo motor. Several other studies use fuzzy logical to control AC motors (Sergaki (2010), Wang, L. and Hong (2011), Zhongke (2004), Zidani and Said (2005)) and Tong-Ying *et. al.* (2004) proposed Wavelet Network for the same purpose. Davari *et. al.* (2012) proposed a sensorless predictive torque control method for an AC motor using sliding mode control with feedback gains assigned by the H-inf method. Huang and Fu (2007) proposed a nonlinear adaptive control to achieve position tracking for AC motors, including a friction compensation mechanism.

In this paper it is proposed a new control algorithm for an industrial AC motor with gear and encoder at the motor shaft and a simple off-the-shelf voltage controlled frequency inverter. The magnetic flux is open-loop controlled based on the input frequency and significant slippage would occur at very low speed or high torque requirements. The goal of this work is to propose a simple control law for allowing position control of the output shaft of the actuator with good robustness and performance, evidenced from the experimental results.

2. EXPERIMENTAL SETUP

The experimental system setup is an actuator composed of an induction motor with gear. An optical incremental encoder is connected to the rotor. The output shaft is connected to a specially built setup depicted in Fig. 1. In Fig. 2(a) the actuator with an incremental encoder at the rotor shaft is shown on the right. The output shaft is perfectly horizontal. There are two identical arms connected to the gear output shaft. The connection detail is shown in Fig. 2(b). Both arms are 1.2*m* long and capable of holding a configurable mass setup with negligible bending. A set of mass cylinders can be attached and firmly fixed with nuts at the far end of each arm.

With this setup it is possible to either set the amount of inertia in the system through the use of cylinders with the same mass on both arms or a combination using different loads at each arm's end. This asymmetric setup moves the load's center of mass out of the output axis and the gravitational forces produce a variable momentum depending on the output position.

The motor is driven by a frequency inverter. The control law runs on a DOS-based PC for single task real-time control. A FPGA-based digital system connects the PC parallel port with the fast transitioning PWM generator and incremental encoder position counter and also generates the interrupt required for the programmed control law. Some analog parts complete the system setup with the required signal conditioning. Figure 3 shows a block diagram of this system.

The frequency inverter is a MOVITRAC LT (http://www.sew-eurodrive.com/) and it is driven by a 0-10V analog signal to produce a three phase rotating magnetic field from 0 to 60*Hz* (velocity control). A digital input sets the rotation direction.

The frequency inverter output current is left in its default *I* x *f* mode. In this mode of operation, the armature current *I* is proportional to the frequency *f*. In this mode of operation, the armature current is defined in open loop, so no slippage control is done at the frequency inverter. The inverter was also configured so that it responds as instantaneous as possible to the input. Experimental data show that the lag to a step velocity signal applied as an input to the system and measured by the motor encoder has an average of 7.5 *ms*, with a jitter of ±2.5 *ms*.

A standard PC is used to run the control law in real-time. For this experiment a 500*Mhz* X86 CPU is used and a MS-DOS program prepares the system for operation and runs the control law. The control law is interrupt activated. The software allows a set of functions to be performed to prepare the system for operation and to store the results. This including reading a time series of points to be used as reference trajectory, enabling and disabling the control, setting initial position (the experimental setup has no absolute position sensor), logging the results and viewing on screen in real-time. The software was made so that no disk I/O or any other interrupt blocking operation are performed during the control. The reference and output positions are stored in RAM while the control is running: a pre-processing stage loads the reference positions from a disk file and a post-processing stage stores the output positions into a given file on disk.

An Altera (http://www.altera.com/) UP-1 (FLEX 10K20 FPGA) board is used to interface the PC through the parallel port (EPP mode). The FPGA implements the EPP parallel port protocol, decodes the incremental encoder pulses, and generates both the direction and the analog signal (through filtering and amplifying an 8 bit PWM modulated signal). The FPGA also implements a timer to sample the encoder position and generates a PC interrupt (through parallel port interrupt support) at a regular interval of 0,65536 *ms* (2^{14}/25*MHz*).

The control routine (software) is shown in the pseudocode depicted in Fig. 4.

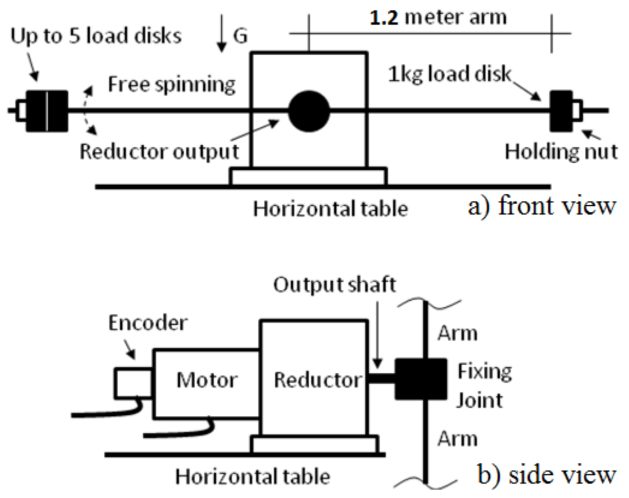

Fig. 1: Experimental setup diagrams.

Fig. 2: Actual setup photograph: Actuator setup with couple arms and output shaft detail.

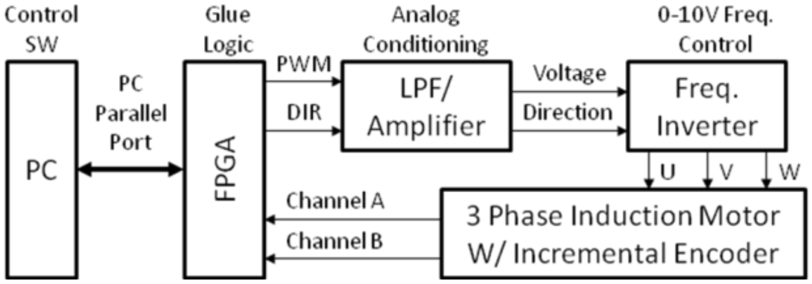

Fig. 3: Control system hardware architecture.

Interrupt

Get output position (hardware interface)

Calculate the output velocity

Get reference position (memory buffer)

Run the control law

Set the new **velocity** and **direction** (hardware interface)

Log control law input and output (memory buffer)

Enable new interrupts

End

Fig 4. Control routine pseudocode.

3. CONTROL LAW

The proposed control law is independent of prior knowledge of a dynamic model of the system. This is an advantage due to the difficulty of performing a dynamic modeling work, especially in cases where the inertia moved by actuators has a complex nature and the actuators have nonlinear friction. The main control objective is to perform a position tracking, i.e., the angular position of the actuator output should follow a reference position.

Initially it is necessary to define a reference position θ_r and a reference speed $\dot{\theta}_r$. θ and $\dot{\theta}$ are the angular position and speed of the actuator output shaft respectively. The control law acts specifying the speed command V_c that will be sent to the drive frequency of the actuator and has the following form:

$$V_c = \dot{\theta}_r + K_v\left(\dot{\theta}_r - \dot{\theta}\right) + f\left(\theta_r, \theta\right) \tag{1}$$

K_v is a gain proportional to the velocity error and $f\left(\theta_r, \theta\right)$ is a function that introduces a component in the control law that depends on the position error. A block diagram of this control law can be seen in Fig 5.

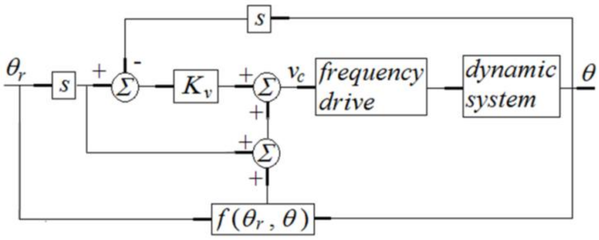

Fig. 5 Block diagram of the proposed control law.

We proposed a simpler correction function, proportional to the position error, including, however, a saturation to ensure stability. The algorithm of the correction function $f\left(\theta_r, \theta\right)$ is described below.

$$\begin{aligned}
& cor_{\lim} \Rightarrow \text{is defined} \\
& \text{err}_{\lim} \Rightarrow \text{is defined} \\
& K_c = \frac{cor_{\lim}}{err_{\lim}} \\
& e_p = \theta_r - \theta \\
& f\left(\theta_r, \theta\right) = K_c e_p \\
& if \;\; f\left(\theta_r, \theta\right) > cor_{\lim}, \\
& \quad f\left(\theta_r, \theta\right) = cor_{\lim} \\
& \quad elseif \;\; f\left(\theta_r, \theta\right) < -cor_{\lim} \\
& \quad f\left(\theta_r, \theta\right) = -cor_{\lim} \\
& end
\end{aligned} \tag{2}$$

The graph of the correction function $f\left(\theta_r, \theta\right)$ can be seen in Fig. 6. $cor_{\lim}$ and $err_{\lim}$ are the correction and position error limits, respectively, K_c is the tangent of β angle (see Fig. 6) and e_p is the position error. The derivative gain K_v must be such that the derivative component (see equation (1)) does not add more than 20% of the maximum velocity (V_{mx}) when the angular velocity error is at maximum. This situation may happen if $\dot{\theta}_r = V_{mx}$ and $\dot{\theta} = 0$. Respecting this limit means no risks of unstable response and it does not inject high frequency noise in the velocity control (the velocity signal obtained from the encoder is noisy). It was verified that the derivative component contributes little to the closed loop system's performance, so that a null K_v generates acceptable performance in the experiments. The parameter cor_{lim} was set at 15% of maximum velocity (V_{mx}) and this percentage is correlated with the torque dead zone of the actuator. Several experimental results were obtained and showed that this value does not compromise the stability of the closed loop. Once established cor_{lim}, the parameter value err_{lim} defines the angle β and this angle is directly related to the performance and stability characteristics of the system. A lower β implies greater err_{lim}, meaning more stability and less performance. Higher β implies smaller err_{lim}, meaning better performance and less stability. Experimental results indicated that err_{lim}=0.035 *rd* gives a good compromise between performance and stability. Once established cor_{lim} and err_{lim}, β will be known and $K_c = tg(\beta)$. All parameters of the control system are shown in Table I (values at the output gearbox side).

Table 1. Parameters used in the control algorithm.

V_{mx} (rd/s)	K_v	K_c (1/s)	cor_{lim} (rd/s)	err_{lim} (rd)
4.512	0.2	7.75	0.676	0.087

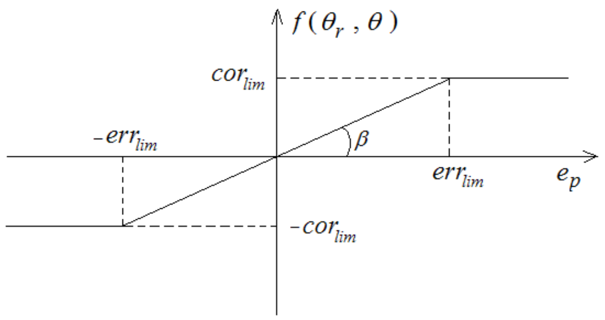

Fig 6. Correction function with saturation.

4. EXPERIMENTAL RESULTS

Experiments were performed with and without load coupled to the actuator's output shaft. Two forms of control were tested: with and without the correction function $f(\theta_r, \theta)$. With the correction function the control is identical to the one showed in Fig 5, defined by the equation (1). Without the correction function the control has the form $V_c = \dot{\theta}_r + K_v(\dot{\theta}_r - \dot{\theta})$ (reference velocity plus a component proportional to velocity error). The experiments with load coupled to the actuator's output shaft were performed in unbalanced manner, with 5 *kg* at the far end of one arm and 4 *kg* at the far end of the other arm (see Fig. 2). This asymmetry of load inertia generates variable load torque and stresses the controller's performance.

The chosen reference trajectory changes its speed sign with low acceleration. This feature adds difficulties to the control law due to nonlinear friction that provokes stick-slip modes when passing through zero speed. Considering $T = 30s$ (period of the sine function), the position reference trajectory has the form:

$$\begin{cases} \theta_r(k) = \dfrac{\pi\, t_k}{T} \sin\left(\dfrac{2\pi}{T} t_k\right) & \text{if } t_k \le T; \\ \theta_r(k) = \pi \sin\left(\dfrac{2\pi}{T} t_k\right) & \text{if } t_k > T; \end{cases} \tag{3}$$

With k=0,1,2,3,… . Reference speed is the time derivative of the equation (3). Figure 7 shows the angular position and velocity reference trajectories. In the firsts ten seconds the angular speed reference has low amplitude and the non-linear friction of the actuator become very important: stick-slip behavior occurs at low speeds, causing difficulties for the control law. The long period of the sine wave causes changes in the speed sign with low accelerations and this also generates stick-slip. Therefore, the reference trajectories were chosen with the intention to better test the control law.

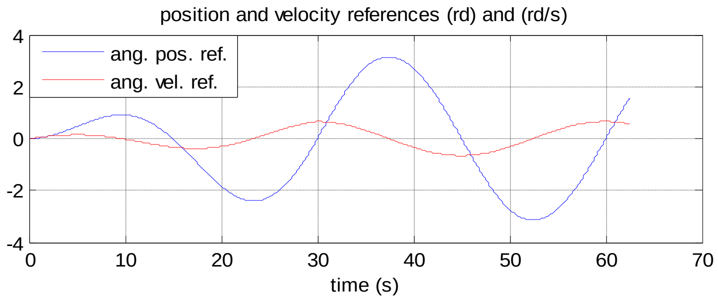

Fig 7. Angular position and velocity reference trajectories.

Figures 8 to 11 show four plots: angular reference position and angular position from the encoder measure (upper left side); angular reference velocity and angular velocity from time derivative of the encoder signal (upper right side); angular position error (bottom left); velocity signal control (V_c) and angular velocity from time derivative of the encoder signal (bottom right).

Figure 8 shows an experimental result without load and control without the correction function $f(\theta_r,\theta)$. At the beginning of the motion, when the sign of the velocity changes with low acceleration, the actuator's nonlinear friction (stick mode) imposes extra difficulties to the control and the error is unacceptable, reaching 1 *rd* (see Gomes *et. al*. (2006) and Gervini *et. al*. (2013) to more information about nonlinear friction).

The experimental results showed in Fig. 9 were obtained with the correction function $f(\theta_r,\theta)$. It can be seen that the position tracking is good. After the initial movement in which the error had reached 0.03 *rd*, the error was restricted to a maximum of 0.01 *rd*, denoting a good performance.

The next two experimental results were intended to test the ability of the controllers to reject external disturbances, maintaining performance. Asymmetry in inertia coupled to the actuator's output shaft generates a variable torque as a function of angular position, which tends to degrade the performance of the used control law.

Figure 10 shows experimental results using the control law without the correction function $f(\theta_r,\theta)$. As it can be seen in this figure, the perturbation imposed by unbalanced load connected to the actuator completely degrades the reference trajectory tracking.

The control algorithm with the correction function $f(\theta_r,\theta)$ has been applied to the actuator with asymmetric load and the experimental results can be seen in Fig. 11. The error increased compared to that shown in Fig. 9, but the performance was maintained. After the start of the movement, the position error was restricted to a maximum of 0.02 *rd*.

Figures 12 and 13 are intended to show the difficulty imposed by the unbalanced inertia to the control laws. Errors without the correction function can be seen in Fig. 12, while the errors using the correction function are seen in Fig. 13. In both figures, the errors are plotted in the cases with and without inertia coupled to the actuator. In fact, these two figures summarize the position errors of figures 8 to 11. From the analysis of these last two figures it is concluded that the disturbance imposed by unbalanced inertia increases the level of tracking error, as expected, but the control law with the correction function remains robust to this perturbation.

Figure 14 shows the reference velocity, the velocity obtained from the encoder signal and the velocity control effectively sent to the frequency inverter, in the cases without load (Fig. 14a) and with asymmetric load (Fig. 14b), both using the correction function $f(\theta_r,\theta)$. A low pass filter was applied on these signals to improve the visualization. This figure clearly shows the correction function which tends to increase the velocity control to compensate nonlinear friction and inertial efforts, including disturbances due to unbalanced load.

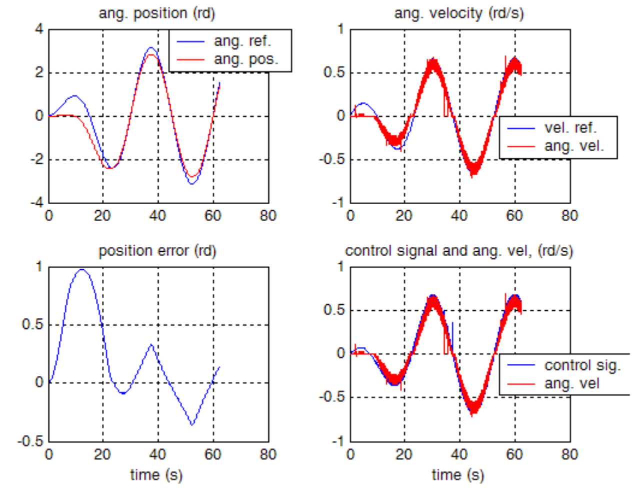

Fig 8. Experimental result without load and control without the correction function $f(\theta_r,\theta)$.

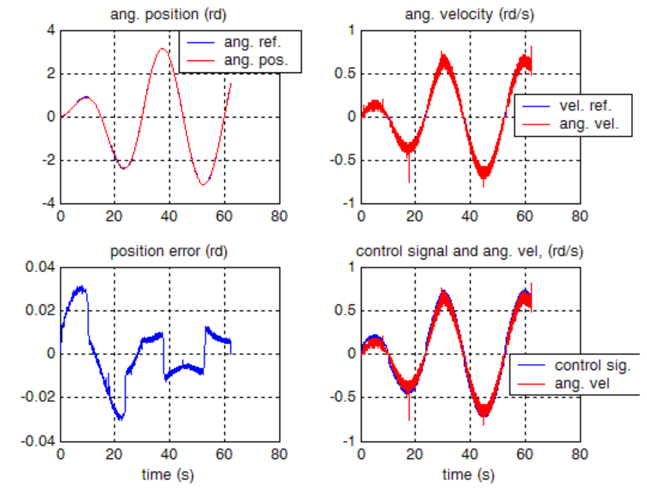

Fig 9. Experimental result without load and control with the correction function $f(\theta_r,\theta)$.

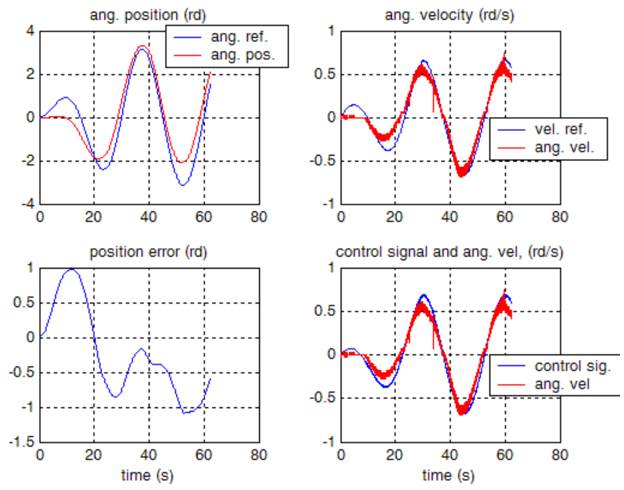

Fig 10. Experimental result with load and control without the correction function $f(\theta_r,\theta)$.

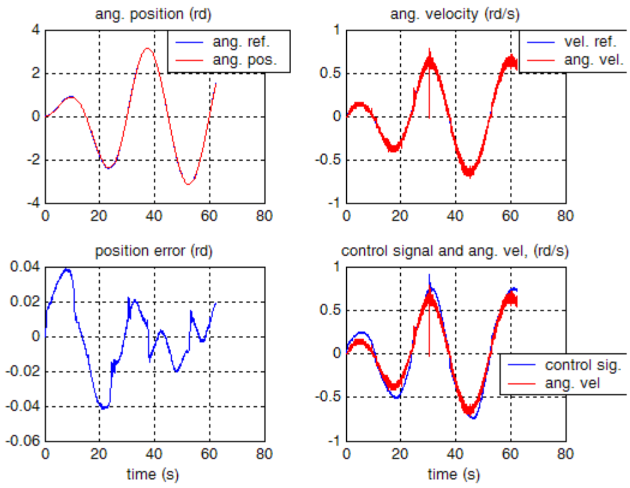

Fig. 11 Experimental result with load and control with the correction function $f(\theta_r,\theta)$.

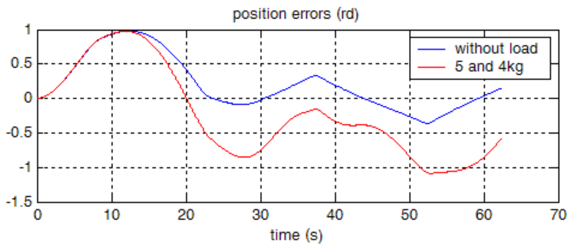

Fig. 12 Errors obtained with control without the correction function $f(\theta_r,\theta)$.

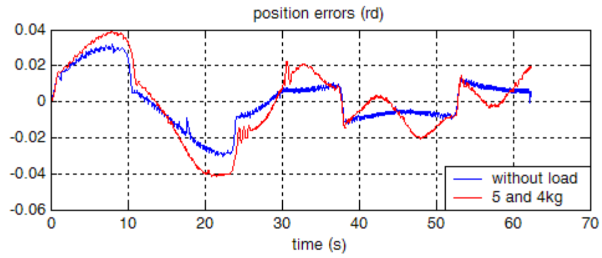

Fig. 13 Errors obtained with control including the correction function $f(\theta_r,\theta)$.

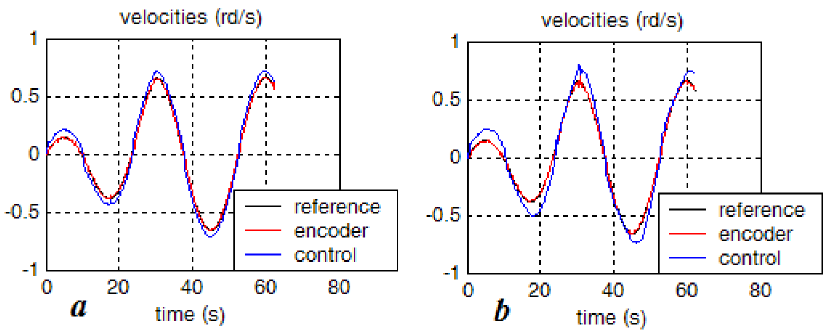

Fig. 14 Control with the correction function $f(\theta_r,\theta)$: a) without load; b) with asymmetric load.

5. CONCLUSÕES

In this paper, a control algorithm for an actuator with AC motors was proposed to allow closed loop position control by means of a standard voltage controlled frequency inverter, with field frequency proportional to the applied voltage. Slippage, variable load and other phenomena in the AC motor-inverter system was ignored in the design of the control law and yet the system performed very well, demonstrating the robustness of the proposed approach. The principle of the control law is simple, consisting of varying the frequency sent to the inverter depending on the position error. Even a disturbance coming from external unbalanced inertia coupled to the actuator's output shaft was not enough to deteriorate the performance of the proposed control law. Besides the simplicity, the control algorithm has the advantage of not requiring prior knowledge of the system's dynamic model and can be very useful for practical implementation of position control in actuators with AC motors. In future work we intend to test other control algorithms for AC actuators such as neuro-fuzzy control, for example.

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7. RESPONSIBILITY NOTICE

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Explicações sobre o parecer do comitê científico

The proposed controller is equivalent to a PD controller with saturation in the derivative action and a feedforward action from the reference. It does not seem reasonable to state that the controller design does not depend on the dynamic model of the system. The experiments were limited and the methodology and analysis do not suggest that. The most that one may conclude is that the control law should be investigated deeply. Please, take action.

Por favor, observem que não se trata de um controle convencional, no qual a saída do controlador é torque. A saída do bloco de controle (ver Fig. 5) é frequência injetada no inversor de frequência e, portanto, não se trata de um controle PD convencional. Esta estratégia de controle tenta diminuir os efeitos do “escorregamento” em frequência, muito comum no controle de motores AC. Os parâmetros da lei de controle são determinados sem a necessidade de conhecimento prévio do modelo dinâmico do atuador, conforme explicado na seção 3. Os resultados experimentais foram amplos e com várias trajetórias de referência diferentes. Colocamos no artigo os resultados com a trajetória de referência que entendemos gerar mais dificuldade para o controle: oscilações em velocidade passando pelo zero com baixas acelerações, trajetória essa que amplifica os efeitos do tipo stick-slip, muito comuns em atuadores com moto-redutoras. Ressaltamos finalmente que são resultados experimentais.

The authors conclude that the derivative component has little influence on the performance of the closed loop and imposed Kv = 0. This reduces the control law to a proportional control with saturation and a feedforward action which probably should be largely responsible for the small error for tracking the reference signal.

Estaria perfeito o raciocínio se o controle fosse um PD convencional, cuja saída é torque. Fizemos muitos experimentos, com muitas trajetórias de referência diferentes. Chegamos à conclusão que os efeitos da função de correção eram suficientes para proporcionar um bom desempenho. Outra, retirando a realimentação de velocidade na lei de controle, diminuíamos o nível de ruído injetado no inversor.

The system stability analysis was done empirically and with a limited scenario. It is suggested to use the system dynamic model in order to determine the stability, for exemple by means of the describing function of the saturation block. By doing so the authors may rigorously conclude if the model is necessary or not.

A tentativa era desenvolver uma estratégia de controle realmente independente do conhecimento prévio de um modelo dinâmico. A estabilidade foi testada na prática, a partir de uma exaustiva repetição de experimentos com diversas trajetórias de referência diferentes. Além das trajetórias diferentes, fizemos experimentos com variações de massa na carga terminal acoplada à saída do redutor do atuador. Os experimentos mostrados no artigo foram sem carga e ainda, com carga desbalanceada (5kg numa extremidade da haste rígida e 4 kg na outra extremidade). Os parâmetros do controle foram mantidos os mesmos e o desempenho foi bom, mesmo diante de resultados com forte variação da inércia acoplada à carga terminal.

During the experiments the authors performed tests without the correction function which is the only part of the control law that takes into account the position error. Thus, one may conclude that it makes no sense to use these results to evaluate the full control law and, therefore, the plots of Fig.8, 10 and 12 and their discussions should be removed.

Os resultados têm a intenção de mostrar a importância da função de correção em evitar o efeito do “escorregamento” em frequência. No lugar desta função de correção, foi testada inicialmente uma correção baseada em lógia fuzzy. Porém, os resultados com a função de correção proposta foram semelhantes aos obtidos com a lógica fuzzy, mas com a vantagem de uma maior simplicidade de projeto e de implementação.

Based on the above the title of this work does not seem to be appropriate.

Acreditamos ser importante ressaltar que a proposta do artigo tem grande utilidade prática, principalmente para quem precisa fazer seguimento de trajetória de referência em posição, utilizando-se de atuadores com motores AC.