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COMPARATIVE ANALYSIS OF CONTROL STRATEGIES APPLIED ON SPEED CONTROL OF SERVOMOTOR USING PID AND FUZZY CONTROLLERS

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Abstract. *This paper presents a solution for the development of speed control for DC servomotors based on data acquisition systems. The servo driver is constituted by a simple and reduced cost integrated circuit with transistorized dual full-bridge controlled by pulse width modulation (PWM) algorithm. The approach proposed is versatile and allows, with relative ease, the evaluation of a variety of digital control algorithms. For demonstrate this, the work presents the design of analog and digital PID controllers tuned by Ziegler-Nichols method, poles cancelling and fuzzy controllers. The results compare the step response obtained by simulation and practical experiments.*

Keywords*: PID control, fuzzy control, motor drive, data acquisition system*

1. INTRODUCTION

Servomotors are usually small and high precision motors which can be used in several engineering applications. They can be found in CD and DVD players, mobile security cameras, microwave ovens, drive control systems of antennas and radars, copying machines, printers, scanners, valves automatically controlled and many other devices.

The servomotors control is used in many industrial applications where satisfactory dynamic behavior and torque, speed or position control with precision are decisive factors for increasing the quality and productivity. This is the case of machine tools, robots, palletized machines, packaging machines, among other applications.

Currently, the growing trend of digital electronics and the production of new technologies and computational tools allow the development of a variety of techniques of control with versatility and with relative ease reproducing various aspects before observed only by simulation (Li and Khan, 2005), (Lima, 2008), (Sousa and Bose, 1994). Within this context, this article presents the application of computational tools and modern equipment at development of speed control of a servomotor including the design and tune of PID and fuzzy controllers (Åstrom and Hägglund, 1995), (Zadeh, 1965), (Ziegler and Nichols, 1942), (Tsoukalas and Uhrig, 1997).

Although the control of servomotors has been thoroughly discussed in the literature, this paper presents as main contribution the use of a modern tool, recently launched in the market, to develop quickly and with relatively ease sophisticated controls, such as fuzzy control. The solution can be used in didactic experiences for engineering courses but also in similar applications in industrial environment.

2. CLOSED LOOP SPEED CONTROL SYSTEM

The speed control system developed consists of the following components:

- permanent magnet DC motor, illustrated at Fig. 1;
- speed sensor which consists of a tachogenerator coupled to motor shaft and a resistive divisor circuit;
- dual full-bridge driver controlled by pulse-width modulation (PWM) as presented at Fig. 2; at this circuit the speed of servomotor is controlled by the duty cicle of PWM signal produced by computer on analog output DA0, the sense for rotation is defined by the analog output DA1 and the speed is measured using the analog input AD0;
- a digital computer, a data acquisition board, electronic interface circuit and a software package that allows to obtain, to analyze and to display the data obtained in the acquisition.

The closed loop speed control system resulting is illustrated at Fig.3 where $G_C(s)$ is the transfer function of the controller, $G_{AQ}(s)$ is the transfer function of the data acquisition system, including data acquisition board and the program, $K_{AC}(s)$ is the gain of the amplifier circuit, neglecting its delay time on response, $G_M(s)$ is the transfer function of servomotor, $G_{MM}(s)$ is the transfer function of speed sensor and its gain $K_{MM}(s)$, and finally $G_L(s)$ is the transfer function of load. The block diagram presents the following variables: $W_R(s)$ and $V_R(s)$ are the speed reference (rad/s or V), $E(s)$ is the deviation of the measured value of speed in relation to the reference (error control), $U(s)$ is the control signal produced by controller, $V_T(s)$ is the voltage applied to DC servomotor, $W_m(s)$ is the speed produced, $V_m(s)$ is the corresponding voltage measured by speed sensor and $W_1(s)$ and $W_2(s)$ are the speed components produced by the voltage applied to servomotor and by the variation of torque $T_C(s)$ produced by the load coupled. Note that the load can´t drive servomotor but only reduces its speed. This means that: $|W_1(s)| \geq W_2(s)$ where $W_2(s) \geq 0$. At this case, generally, the speed $W_m(s)$ can be obtained by:

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$$W_M(s) = signal(W_1(s)) * \max\left(\left(\left|W_1(s)\right| - W_2(s)\right), 0\right) \tag{1}$$

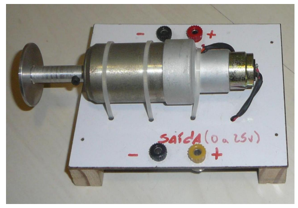

Figure 1. DC Servomotor

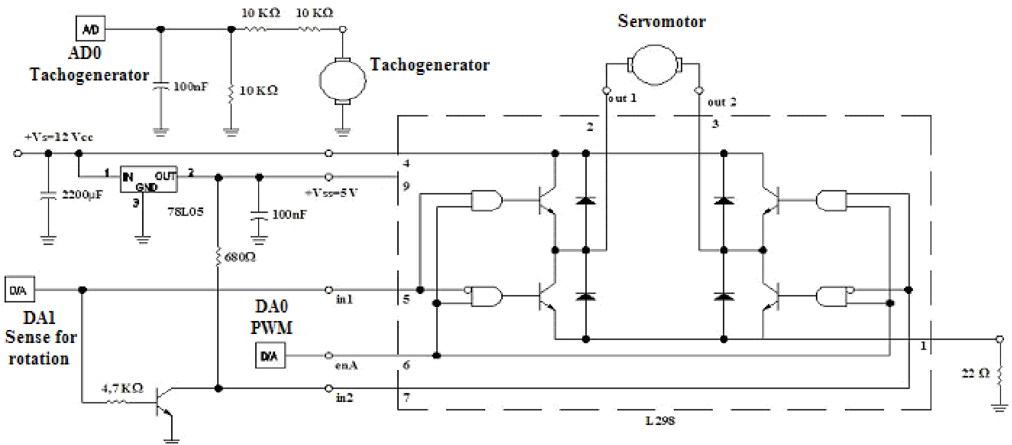

Figure 2. Amplifier circuit for drive the DC servomotor

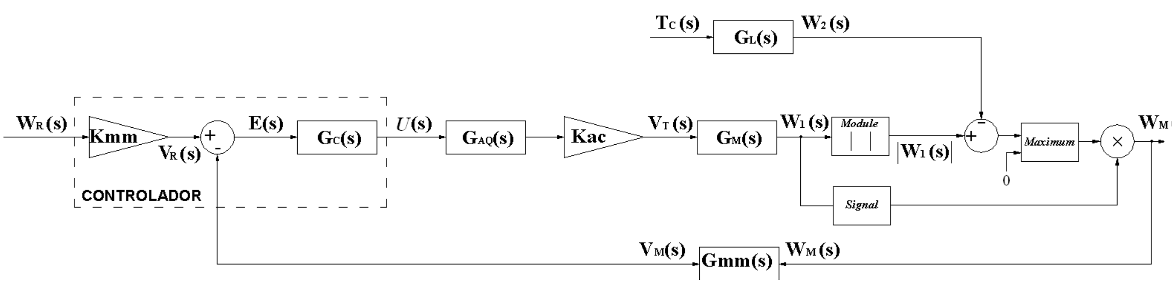

Figure 3. Block diagram of closed loop speed control system

Using the parameters obtained by the manufacture's manual it gets:

$$G_M(s) == \frac{W_1(s)}{V_t(s)} = \frac{5.0149\text{x}10^7}{\left(s + 7.5496\text{x}10^3\right)\cdot\left(s + 1.4272\text{x}10^2\right)} \tag{2}$$

$$G_{MM}(s) = \frac{V_m(s)}{W_m(s)} = \frac{5.8714\text{x}10^4}{\text{s} + 4.3229\text{x}10^6} \tag{3}$$

$$G_L(s) = \frac{W_2(s)}{T_c(s)} = \frac{-\left(1.523\text{x}10^5 \cdot s + 1.172\text{x}10^9\right)}{s^2 + 7.6924\text{x}10^3 s + 1.078\text{x}10^6} \tag{4}$$

In (3) is possible to deduct the gain of the meter given by K_{MM} = 0.013582. The parameter of the amplifier circuit was obtained using the manufacture's datasheet getting $K_{AC}(s)$ = 12. The data acquisition system transfer function estimated by testing results:

$$G_{AQ}(s) = \frac{1.2}{s + 1.2} \tag{5}$$

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Neglecting the variations in load, the transfer function which relates the rotation of servomotor with changes to the speed reference value is given by:

$$\frac{W_1(s)}{W_R(s)} = \frac{K_{MM} \cdot G_C(s) \cdot G_{AQ}(s) \cdot K_{AC}(s) \cdot G_M(s)}{1 + G_C(s) \cdot G_{AQ}(s) \cdot K_{AC}(s) \cdot G_M(s) \cdot G_{MM}(s)} \tag{6}$$

Neglecting the reference value or assuming the operation with constant voltage reference, it gets the transfer function which relates the speed motor with the variations in torque load:

$$\frac{W_2(s)}{T_c(s)} = \frac{G_L(s)}{1 + G_C(s) \cdot G_{AQ}(s) \cdot K_{AC}(s) \cdot G_M(s) \cdot G_{MM}(s)} \tag{7}$$

Note that Eq. 6 and Eq. 7 have the same denominator (characteristic equation).

3. DATA ACQUISITION AND COMPUTATIONAL CONTROL ALGORITHM

The control algorithm is developed at computer using the educational kit ELVIS™ (Educational Laboratory Virtual Instrumentation Suite). This kit, illustrated at Fig. 4, is constituted of a data acquisition board (DAQ) programmable by software based on LabVIEW™, a multifunctional device and a workstation with protoboard where the user can develop the applications (Li and Khan, 2005).

The control algorithm includes the following functions:

- produce the PWM signal and define the sense for rotation; note that the sense for rotation depends on the PWM signal (DA0) and the signal on DA1 produced on algorithm and sent to amplifier circuit (Fig. 2);
- a dead time, purposely inserted in the program to avoid short circuit in the amplifier circuit when reversing the direction of rotation; this strategy ensures that the voltage on the base of the transistor is kept to zero during a time when there is reversal in the direction of rotation;
- digital control algorithm constituted by PID or fuzzy controller which uses the measured voltage by AD0 that depends on the voltage at tachogenerator (Fig. 2).

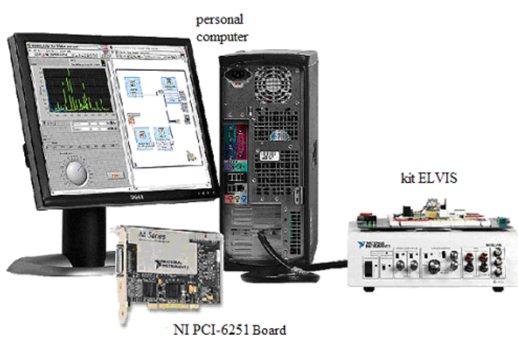

Figure 4. Data acquisition system using kit ELVIS™

To evaluate the efficiency of the modeling was made the simulation of the system, even without the introduction of controller, using a step at input voltage ($V_R(s)$ = 10/s) and measuring the voltage produced by speed sensor $V_m(s)$. After this, it gets a practical test using the data acquisition system (Fig. 4). The results obtained by simulation and by practice are illustrated at Fig. 5. Note the similarity in the responses, showing the efficiency of modeling performed.

4. STABILITY ANALYSIS

The gain limit of the controller is defined as the highest proportional gain that can assumed at system, without integral and derivative actions, where the system remains on its threshold of stability. For this, considering only the proportional mode on controller at Eq. 6 and substituting the parameters of system it gets, after some calculations:

$$\frac{W_1(s)}{W_R(s)} = \frac{9.8082\text{x}10^6\left(\text{s} + 4.3229\text{x}10^6\right)K_c}{s^4 + 4.3306\text{x}10^6\text{s}^3 + 3.326\text{x}10^{10}\text{s}^2 + 4.7\text{x}10^{12} \cdot \text{s} + 5.5921\text{x}10^{12} + 4.24\text{x}10^{13} K_c} \tag{8}$$

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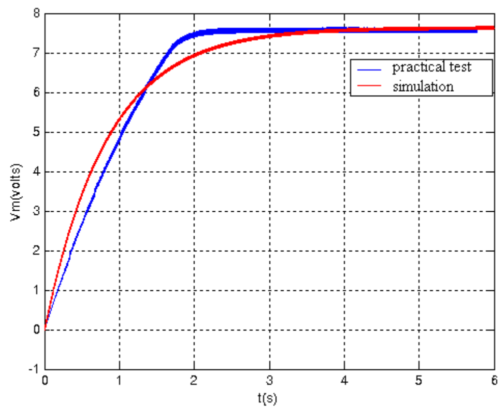
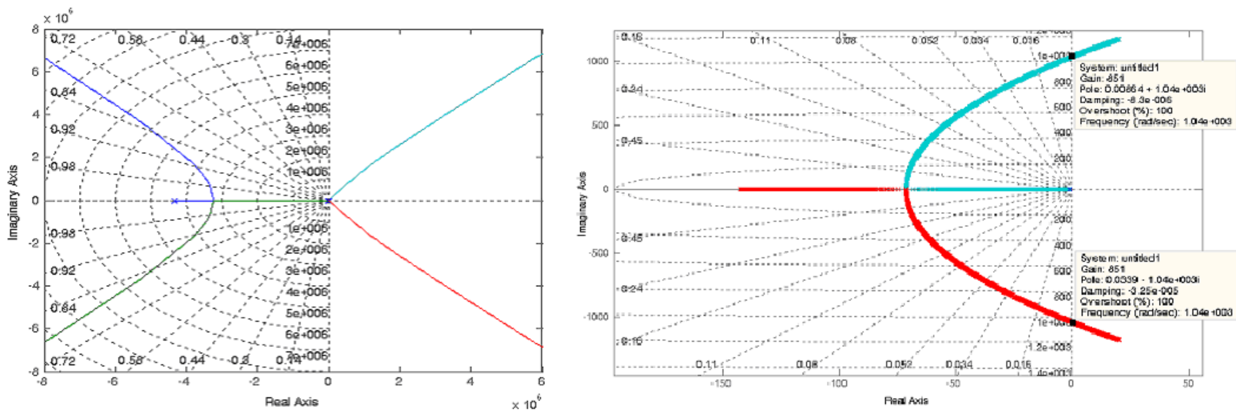


Figure 5. Comparison of step response – simulation x practical test with data acquisition system

The denominator of the equation above represents the characteristic equation of the closed loop system. Considering only the proportional mode on controller and using the Routh's criterion of stability was calculated the gain limit $K_C = K_{CU} = 851.1458$, which can be confirmed by simulation of root locus of the system, as illustrated at Fig. 6. At this figure, the critical period, $\omega_{CU} = 1.0418 \times 10^3$ rad/s, was also obtained.



(a) (b)

Figure 6. Root locus of closed loop speed control system (a) Complete root locus (b) Part of root locus with zoom

5. PID CONTROL

In recent years new modern methods of control have been used, such as fuzzy control, neural networks and neuro-fuzzy controllers among others. However, about over 90% of control loops still use industrial PID controllers (Åstrom and Hägglund, 1995). But it is known that the majority of these loops operate poorly tuned, creating additional costs that could be minimized. This justifies the importance of the tune of controllers (Åstrom and Hägglund, 1995).

The PID controller combines the proportional, integral and derivative components obtaining the classical equation which can be seen below:

$$m(t) = K_P\left(e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{de(t)}{dt}\right) \tag{9}$$

where K_P is the proportional gain, T_i is the integration time constant and T_d is the derivation time constant. Assuming zero on initial conditions and applying the Laplace transform we have the transfer function of PID controller:

$$\frac{M(s)}{E(s)} = K_P\left(1 + \frac{1}{sT_i} + sT_d\right) = K_P\left(\frac{1 + T_i s + T_i T_d s^2}{T_i s}\right) \tag{10}$$

At literature there are several methods for tuning of PID controllers, such as the method of continuous oscillations by Ziegler-Nichols (Ziegler and Nichols, 1942), method of direct synthesis, method of canceling poles (Lima, 2008), etc.

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At this work are presented the tuning of PID controller using the method proposed by Ziegler and Nichols and the method of canceling poles.

5.1. Ziegler-Nichols Method

At this method the value of the PID parameters are functions of the gain limit of controller K_{CU} and its corresponding critical period and provide a reduction to ¼ of value between the first and second peaks of the step response in closed loop. Table 5.1 presents the values of parameters for P, PI, PD and PID controllers as suggested by Ziegler-Nichols method. All proposed controller were tested (P, PI, PD, PID), using classical or modified algorithm. The controllers at Eq. 11 and Eq. 12 were chosen because they present the best performance at step response.

$$G_{PD1}(s) = 510.7\left(1 + 7.5389\text{x}10^{-4}\, s\right) \tag{11}$$

Table 5.1. Parameters values for PID controllers by Ziegler-Nichols method.

Controller	K_C	T_i	T_d
P	0.5 K_C	-	-
PI	0.45 K_C	P_U / 1.2	-
PD	0.6 K_C	-	P_U / 8
PID	0.6 K_C	P_U / 2	P_U / 8

5.2. Canceling Poles Method

It is known that the stability of a linear system is directly linked to the location of closed loop poles in the complex plane *s*. A simple technique for calculating the parameters of a controller is the cancellation of the dominant pole of the system. Although, in practice we will not really mathematically cancel the pole, since the poles of real systems have variable parameters, but is expected to minimize its effects.

At the project the goal imposed is obtain a second order system with damping coefficient ξ=0,358 producing overshoot around 30%. It was designed controllers P, PI and PID using the canceling poles method. The controllers P and PI presented better result at this case.

In order to simplify the model of system, discarding the smaller time constant of motor at Eq. 2, results**:**

$$G_{MAprox}(s) = \frac{46.5204}{7.0067\text{x}10^{-3}\, s + 1} = \frac{6639.3914}{\left(s + 1.4272\text{x}10^{2}\right)} \tag{12}$$

Using the denominator of transfer function from Eq. 5 and neglecting the component relative to sensor, follows:

$$A(s) = 1 + G_C(s) \cdot G_{AQ}(s) \cdot K_{AC} \cdot G_{MAprox}(s) \cdot K_{MM} = 0 \tag{13}$$

Substituting the transfer functions of each component results:

$$1 + G_c(s) \cdot \frac{1.2}{s + 1.2} \cdot 12 \cdot \frac{6639.3914}{s + 1.4272 \cdot 10^2} \cdot 0.013582 = 0 \tag{14}$$

In order to design a proportional controller, considering therefore $G_C(s) = K_C$, it gets:

$$s^2 + 143.92 \cdot \text{s} + 171.264 + 1298.5375 \cdot K_c = 0 \tag{15}$$

Comparing Eq. 15 with the canonical equation for second order systems ($\text{s}^2 + 2 \cdot \xi \cdot \omega_n \cdot \text{s} + \omega_n^2 = 0$) and considering ξ= 0.358 results ω_n = 201.0056 rad/s and the proportional controller:

$$G_{P1}(s) = 30.98 \tag{16}$$

In order to design a proportional integral controller it was considered the PI controller above, where the zero of transfer function will mathematically cancel the dominant pole of system:

$$G_C(s) = G_{P1}(s) = \frac{K_c(s + 1.2)}{s} \tag{17}$$

where T_i = 0.8333 s.

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Substituting the transfer functions of each component at Eq. 13 and including Eq. 17, results, after some manipulations:

$$s^2 + 142.72 \cdot s + 1298.5375 \cdot K_c = 0 \tag{18}$$

Again comparing Eq. 18 with the canonical equation for second order systems ($s^2 + 2 \cdot \xi \cdot \omega_n \cdot s + \omega_n^2 = 0$) and considering $\xi = 0.358$ results $\omega_n = 199.3296$ rad/s and the proportional gain of controller $K_C = 30.598$, results:

$$G_{PI1}(s) = \frac{30.598(s + 1.2)}{s} \tag{19}$$

6. DIGITAL PID CONTROL

Several techniques are available for design and tune digital PID controllers. They can be designed using the same methods proposed by Ziegler-Nichols as previously used for design of classical PID controllers.

The closed loop digital speed control system is illustrated at Fig. 7 where *HG(z)* is the discrete transfer function of system including servomotor, amplifier circuit, data acquisition system and zero order hold *(H(s))* and $F(W_1(z), W_2(z))$ is obtained after to discrete the non-linear equation (1). Using this block diagram it gets the transfer function $W_m(z)/W_m$ given by:

$$\frac{W_m(z)}{W_R(z)} = \frac{K_{MM} \cdot G_C(z) \cdot Z\left[H(s) \cdot G_{AQ}(s) \cdot K_{AC}(s) \cdot G_M(s)\right] . F(W_1(z), W_2(z))}{1 + G_C(z) \cdot Z\left[H(s) \cdot G_{AQ}(s) \cdot K_{AC}(s) \cdot G_M(s) \cdot G_{MM}(s)\right] . F(W_1(z), W_2(z))} \tag{20}$$

$$\frac{W_m(z)}{W_R(z)} = \frac{K_{MM} \cdot G_C(z) \cdot HG(z) . F(W_1(z), W_2(z))}{1 + G_C(z) \cdot HG(z) . F(W_1(z), W_2(z))} \tag{21}$$

In order to choose the sampling time (T) it was considered the criterion (Isermann, 1992) where its value must be less than 10% of the largest time constant of the system τ=8,3333.10^{-2}. The value adopted was T = 1 ms.

The discrete transfer function *HG(z)* can be calculated, assuming T = 1 ms and the parameter of system, resulting:

$$HG(z) = \frac{4.072\text{x}10^{-5} z^4 + 4.088\text{x}10^{-4} z^3 + 7.408\text{x}10^{-4} z^2 + 1.973\text{x}10^{-5} z + 5.544\text{x}10^{-17}}{z^4 - 1.8663 z^3 + 0.8669 z^2 - 4.5577\text{x}10^{-4} z} \tag{22}$$

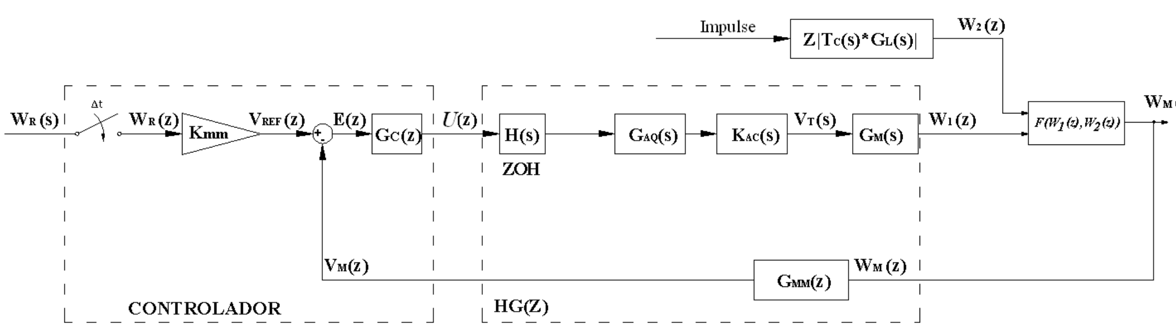

Figure 7. Block diagram of closed loop digital speed control system

The characteristic equation of the discrete time system, neglecting the load is given by:

$$1 + G_C(z) \cdot HG(z) = 0 \tag{23}$$

Substituting (22) in (23) and considering that $G_C(z)$ is a proportional gain, is possible to determine the highest proportional gain that can assumed at discrete system, without integral and derivative actions, where the system remains on its threshold of stability. At the discrete system it can be used the modified method of Routh that requires the transformation of the complex plane *z* to another complex plan called *w* through a bilinear transformation defined by:

$$z = \frac{(w+1)}{(w-1)} \tag{24}$$

After complete this bilinear transformation, the Routh's criterion of stability allows to define the gain limit $0 < K_{CU} < 198.66$, which can be confirmed by simulation of root locus of the system. At this figure, the critical period, $\omega_{CU} = 491$ rad/s, was also obtained.

6.1. Digital PID Controller

In order to design digital PID controllers it is necessary to solve the differential equation (Eq. 9) and transform it into a computationally implementable equation. Several approaches can be used, generating different algorithms such as Euler method, the backward-difference rule and the Tustin method.

The backward-difference method the integral of error is substituted by a sum of errors, and a derivative by a difference as demonstrated below:

$$\int_o^t e(t)dt \cong \sum_{i=1}^{k} e(i) \cdot \Delta t \tag{25}$$

$$\frac{de(t)}{dt} \cong \frac{e(k) - e(k-1)}{\Delta t} \tag{26}$$

Substituting in Eq. 9 it gets, after some manipulation the digital PID algorithm called positional (Eq. 27), since the output of the controller represents the final position of the element of control:

$$U(z) = K_c \cdot \left(1 + \frac{\Delta t}{T_i}\frac{z}{(z-1)} + \frac{T_d}{\Delta t}\frac{(z-1)}{z}\right) \cdot E(z) \tag{27}$$

6.2. Digital PID Controller Tuned by Ziegler-Nichols

At the Ziegler-Nichols method the value of the PID parameters are functions of the gain limit of controller K_{CU} and its corresponding critical period but calculated at the discrete transfer function of system. All proposed controller were tested (P, PI, PD, PID), using positional PID algorithm (Eq. 26) where the parameter were calculated using Table 5.1. The controllers at Eq. 28 and Eq. 29 were chosen because they present the best performance at step response.

$$G_{PID1} = 119.196\left(1 + \frac{1x10^{-3} \cdot z}{0.0064(z-1)} + \frac{0.0016(z-1)}{1x10^{-3} z}\right) \tag{28}$$

$$G_{PD2} = 119.196\left(1 + \frac{0.0016(z-1)}{1x10^{-3} z}\right) \tag{29}$$

7. FUZZY CONTROL

The theory of fuzzy sets was presented in Zadeh (1965) proposing an extension of the concepts of classical theory of sets. The fuzzy logic developed from the theory of fuzzy sets has been used successfully in 1974 by E. H. Mandami and S. Assilian for Control of a steam machine after many attempts with various others techniques, including PID controller. After this, several applications have been developed using fuzzy control, as for example Sousa and Bose (1994) and Tsoukalas and Uhrig (1997), in some cases with the advantage of presenting a good performance when there is presence of non-linearity in the system.

Several fuzzy controllers were designed considering different membership functions and rule base. The solution that presented best performance includes two inputs (error and derivative of error) with gains K_{PF} and K_{dF}; and one control output with gain K_{oF}. The defuzzifier applied uses the method of centroid and the max-min Mandami inference to evaluate the rules. All the gains were adjusted by trial and error using simulation tools. The universe of discourse of all variables were standardized in the interval [-1 1]. The following terms were associated to the membership functions: NL – negative large; NS – negative small; N – negative; Z – zero; P – positive; PS – positive small; PL – positive large.

The membership functions used are illustrated at Fig. 8. The block diagram for simulation the system is illustrated at Fig. 9. The parameters of fuzzy controller adjusted were: $K_{PF} = 0.01$, $K_{dF} = 1x10^{-7}$ and $K_{oF} = 250$.

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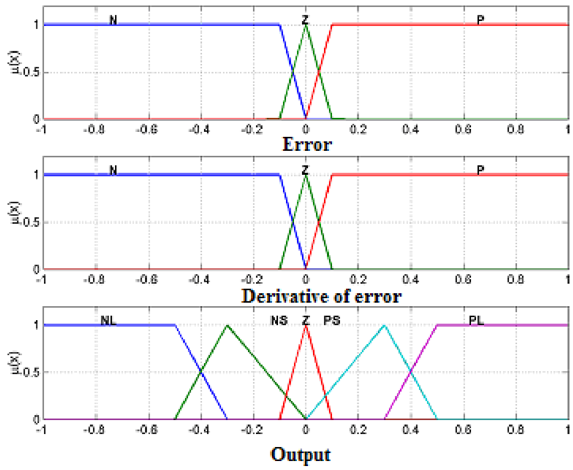

Figure 8. Membership functions of fuzzy controller

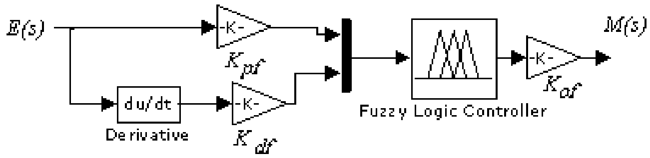

Figure 9. Block diagram of the fuzzy controller

In the fuzzy controller developed, the rule base was established from the experience of the designer and based on expected behavior for the control of speed of servomotor, resulting in the following set of rules:

- R1: if "error is N" and "derivative of error is N" then "output of controller is NL";
- R2: if "error is Z" and "derivative of error is N" then "output of controller is NS";
- R3: if "error is P" and "derivative of error is N" then "output of controller is Z";
- R4: if "error is N" and "derivative of error is Z" then "output of controller is NS";
- R5: if "error is Z" and "derivative of error is Z" then "output of controller is Z";
- R6: if "error is P" and "derivative of error is Z" then "output of controller is PS";
- R7: if "error is N" and "derivative of error is P" then "output of controller is Z";
- R8: if "error is Z" and "derivative of error is P" then "output of controller is PS";
- R9: if "error is P" and "derivative of error is P" then "output of controller is PL".

8. PRACTICAL AND SIMULATION RESULTS

The response of the system was obtained by simulation and practical experiments using the PID controllers $G_{PD1}(s)$ (Eq. 11), $G_{PI}(s)$ (Eq. 16), $G_{PI1}(s)$ (Eq. 19), $G_{PID1}(s)$ (Eq. 28), $G_{PD2}(s)$ (Eq. 29) and the fuzzy controller (Fig. 9). However, the practical response obtained by the controllers $G_{PI1}(s)$ and $G_{PID1}(s)$ that include integral component, were not as expected. The analog output from data acquisition system presents voltage limited to ± 10 V, which will probably be exceeded on some occasions in the control system, resulting on saturation. This effect can significantly modify the behavior of the system and may also produce instability. For minimize the effect of saturation due the integration of error signal, the control algorithm includes an anti-windup control method as illustrated at Fig. 10. The strategy is basically to eliminate the effect of integration for values of the control signal $M(s)$ which results in saturation. At figure, $U(s)$ is the control signal produced by controller after saturation.

The step response simulation obtained by the speed control system using the controllers $G_{PD1}(s)$, $G_{PI}(s)$ and $G_{PI1}(s)$ are illustrated at Fig. 11. The step response simulation obtained by the speed control system using the controllers $G_{PID1}(s)$, $G_{PD2}(s)$ and the fuzzy controller are illustrated at Fig. 12. All the results were obtained considering saturation on control signal and including an anti-windup control in the cases with PID and PI controllers where gain adjusted experimentally were $k_f = 1$ in PID control and $k_f = 0.5$ in PI control. Both responses were obtained using step function with amplitude $V_{REF} =$ 7.6 V. Note that, as expected, the controller with better performance was the fuzzy controller

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which presented fast response and relatively low oscillation. The P and PI1 controllers also present a high performance in speed control. The PID1 and PD2 show very quick response, however it present oscillation in response due the presence of non-linearity in the system. The responses obtained by simulations were evaluated by criteria based on the integral of error: the integral of the absolute error multiplied by time (ITAE criteria) and the integral of quadratic error multiplied by time (ITSE criteria) (Lima, 2008). Again it was observed the better performance on fuzzy controller, followed by P1 and PI1 controllers. The worst performance was obtained by PID1 and PD2 controller due to oscillation in the response.

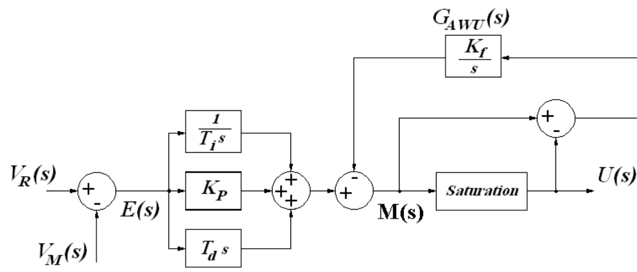

Figure 10. Block diagram of PID controller with anti-windup

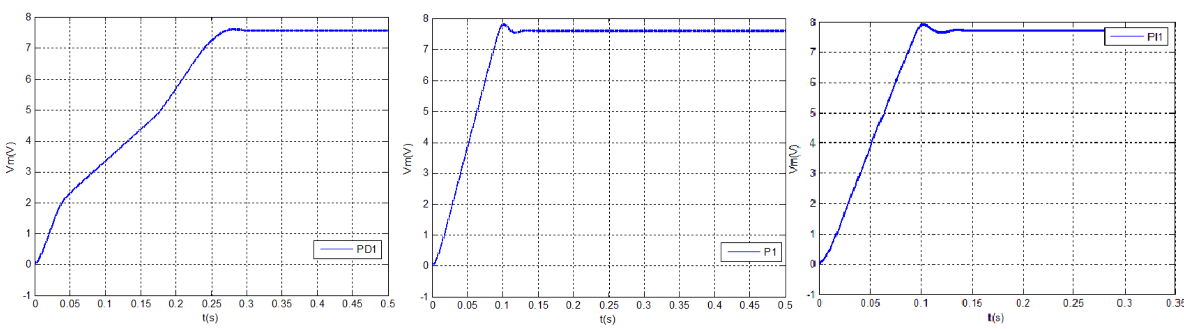

Figure 11. Step response of speed control system using controllers designed by Ziegler-Nichols method and poles cancelling – simulation using step at V_{REF} with amplitude 7.6

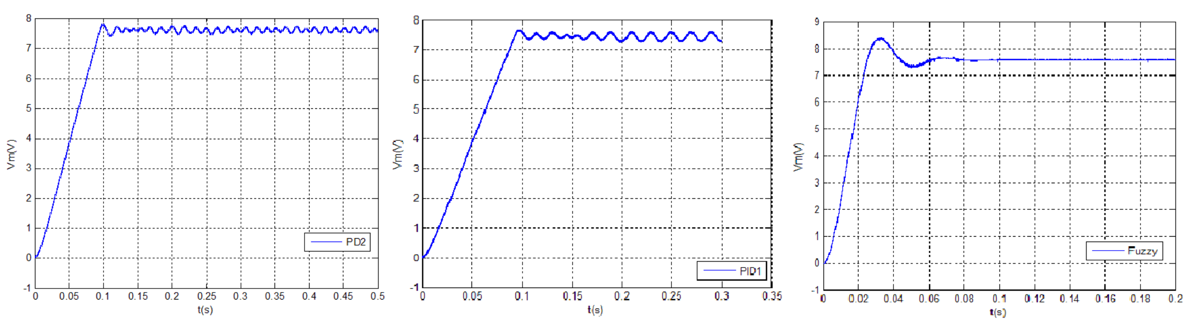

Figure 12. Step response of digital speed control system using controllers designed by Ziegler-Nichols method and fuzzy controller – simulation using step at V_{REF} with amplitude 7.6

The practical result obtained by the speed control system using $G_{PD1}(s)$, $G_{P1}(s)$ and $G_{PI1}(s)$ are illustrated at Fig. 13. The practical result obtained by using $G_{PID1}(s)$, $G_{PD2}(s)$ and the fuzzy controller are illustrated at Fig. 14. Note that, comparing the waveforms at Fig. 13 and Fig. 14, the performance on fuzzy control is a little better than others controllers. As expected, the fuzzy control, presents high performance for systems with non-linearity. The digital controllers present better results than these designed in Ziegler-Nichols and pole canceling in continuous time, because it consider the sampling time used by data acquisition system.

Finally it is observed that the real system is much slower than in the simulation due to several issues not considered at simulation, such as: non-linearity in the electronic drive circuit, effect of introduction sampling in data acquisition do not considered for controllers $G_{PD1}(s)$, $G_{P1}(s)$ and $G_{PI1}(s)$ at simulation, delay on PWM algorithm, the presence of load, even reduced, in the motor shaft, among others.

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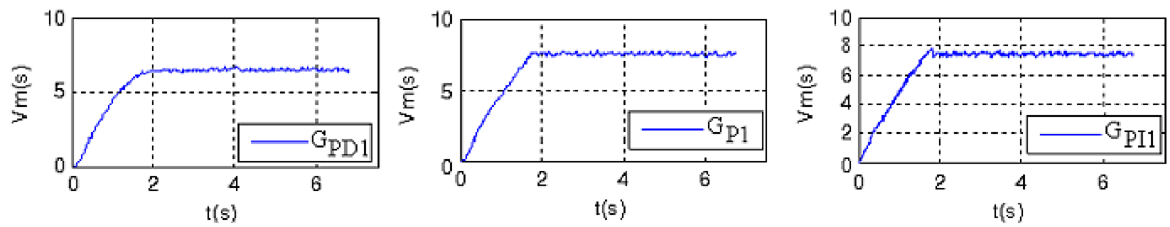

Figure 13. Step response of speed control system using controllers designed by Ziegler-Nichols method and poles cancelling – practical test with data acquisition system and using step at V_{REF} with amplitude 7.6

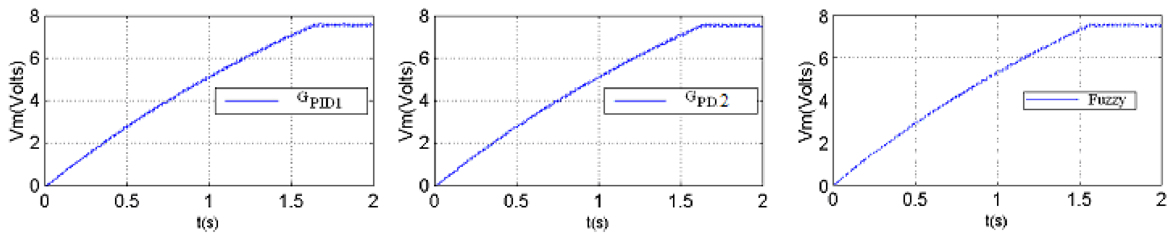

Figure 14. Step response of digital speed control system using controllers designed by Ziegler-Nichols method and fuzzy controller – practical test with data acquisition system and using step at V_{REF} with amplitude 7.6

9. FINAL COMMENTS

This paper presented a methodology for the development of speed control for DC motors. The proposal uses a data acquisition system programmed by computer, a servomotor with speed sensor and a simple and reduced cost dual full-bridge driver.

The approach shows the methodology of modeling the system and the design of PID and fuzzy controller. The results show the applicability of the solution.

The results obtained shows that, in general, the fuzzy controller, if well designed, can provide better performance than PID controllers at the practical system and in the simulation, mainly due the presence of non-linearity such as the saturation of the control signal.

The experiments presented can be used in the teaching experience for engineering courses, involving concepts in the areas of instrumentation, control of continuous process, power electronics and drive electrical machines, among others.

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11. RESPONSIBILITY NOTICE

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