Characterization of Modified PID Controllers to Improve the Response Time of Angular Velocity to the Voltage Step in DC Motors by Means of a Mathematical Model Diagram Using SIMULINK Software

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Abstract. The objective of this research was the characterization of modified PID controllers to improve the response time of direct current (DC) motors. The Degem System EB-109 experimentation module (includes DC motor and six-pole pair synchronous motor), Tektronix TDS 2012 oscilloscope, Fluke 175 multimeter and a simulation environment for block diagrams with Simulink software were used. The procedure began by making voltage and current measurements in the armature of the DC motor in order to calculate its mechanical-electrical constants and obtain its mathematical model. Then, using block diagrams, a closed-loop control system was designed for the DC motor, using the PID as a control block in a first phase, and then in a second phase, the modified PID. The system was analyzed with simulation software and the results of both phases were compared. With the modified PID controller, a better speed and stability response time was obtained, thus eliminating transient peaks.

1. Introduction

Technological innovation in any energy parameter is of vital importance to achieve better performance in the equipment and machines of the production processes [1]; [2]; [3]. Direct current (DC) motors, due to their high starting torque, are used as electric drivers in a variety of activities both in the industrial and residential sectors, having the ability to control and regulate their speed with precision [4]; [5]; [6]. The industrial sector has been growing sustainably through time and automatic control techniques, complying with the requirement and functionality, improving safety, production costs and obtaining efficient results [7]; [8]; [9].

Electric motors are used for a wide variety of residential, commercial and industrial operations, for this reason analysis of the operating parameters of DC motors is performed to improve starting speed response [10].

DC motor feedback systems require electromechanical sensors in control system configurations such as PID, PI and others in order to determine the position of the rotor and calculate an important parameter such as speed to achieve an improvement in performance and efficiency [11]; [12]; [13]. The correct selection and adjustment of the PI and PID controllers allows to obtain a higher performance as a function of the proportional gain parameters Kp and the integral time (Ti) [14].
The classic PID control is an accessible option due to its possibility of regulation of the position and speed immediately and as the most common alternative [15]; [16]. In addition, its analog implementation is simple and does not require large costs in components, while digital controllers integrate hardware-software that can be private or “open source”, they are also very useful in the automation of industrial processes [17] cited by [18]; [19].

Three forms of control intervene in the PID configuration: Proportional control (P) that calculates a value proportional to the current error (difference between the reference value and the feedback value); the integral control (I) that takes the data of the past error and integrates it in time, and the derivative (D) that calculates the derivative of the error in the current time by drawing a projection of the future error. Consequently, in the implementation of a PID controller it will be required to use regulation constants $K_p$, $K_i$ and $K_d$ for the control action and obtain a system output with a fast rise time and a fast settling time cited by [20]. Likewise, to determine the stability of the system, the closed-loop equivalent transfer function is determined using the Routh-Hurwitz criterion [21]; [22]; [23] and [24]. The existence of other method methods such as Tyreus-Luyben also allow the test of the closed loop method of Ziegler-Nichols, relatively changing the calculation of the parameters, but which are based on a gain of the period and the sustained oscillation [25]. The configuration that can be established in a PID can be slightly modified to improve its performance depending on the response to be obtained, as proposed by Eitelberg, who incorporated prior gain blocks to each controller, cited by [26].

Figure 1 shows the diagram of a closed loop PID control with unity feedback where $x(t)$ represents the reference signal or set-point, $y(t)$ the output variable to be controlled, the PID control block is made up of $K_p$ the proportional gain of the proportional control, $K_i$ the integral gain of the integral control, $K_d$ the derivative gain of the derivative control, $e(t)$ is the error signal, $u(t)$ the output of the PID control block that performs the action of control, $F$ is the transfer function of the plant, $Q$ represents the disturbance. The block to be optimized is the classic PID that will be replaced by a modified PID indicated in figure 6. Equation (1) is the formula for the classic PID controller, the formula for the modified PID controller is indicated in the equation (39).

\[
    u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt}
\]  

The present work aimed to compare the speed response time of the DC motor model in a classic closed-loop PID control system with a modified PID control system.

2. Materials Methods

2.1. DC motor parameters

The DC motor parameters were calculated using the EB-109 DEGEM SYSTEM module, figure 2 shows a diagram that is part of the module and was used to measure the rotational speed of the DC motor that is fed by a variable voltage $V_a$, the speed of rotation is transmitted to a synchronous generator of 6 pairs of poles using pulleys and delivering, the generator, an alternating voltage whose magnitude is proportional to its speed of rotation, this alternating voltage is rectified and filtered, obtaining a direct voltage $V_{DC}$ proportional to the rotational speed of the DC motor and also at variable voltage $V_{a*}$.
Figure 2. Angular speed measuring motor-generator diagram of the EB-109 module [27].

The ratio of the diameters of the synchronous generator pulleys \( d_{AC} \) and the DC motor \( d_{DC} \) is \( d_{AC}/d_{DC} = 5.3 \), also the relationship of the angular speeds of the DC motor \( N_D \) and the synchronous generator \( N_S \) is shown in equation (2), angular velocity of generator \( N_S \) and the voltage continues \( V_{DC} \) in equation (3):

\[
\frac{N_D}{N_S} = 5.3 \quad (2)
\]
\[
\frac{N_S}{V_{DC}} = C_1 \quad (3)
\]
\[
\frac{N_D}{V_{DC}} = C \quad (4)
\]

From equations (2) and (3) we obtain equation (4), where \( C = C_1(5.3) \).

To calculate the constant \( C \), the direct voltage \( V_{DC} \) and the wave period \( T \) of the alternating signal of the generator were measured, the Fluke 175 multimeter and the Tektronix TDS oscilloscope were used respectively, measuring the time periods on their screen and through cursors between every 2 wave peaks. It should be noted that these measurements are not exact for the same reason that the instruments have tolerances to their precision and on the oscilloscope screen with the use of the cursors there are also measurement errors. These measurements will allow us to calculate the rotational speed of the DC motor in rpm \( N_D \), which by relating it to \( V_{DC} \) we will obtain the constant \( C \) whose value will be approximate due to the tolerances in the precision of the measurements.

| \( V_{DC} \) (V) | \( T \) (ms) | \( F \) (Hz) | \( N_S \) (rpm) | \( N_D \) (rpm) |
|-----------------|-------------|-------------|----------------|----------------|
| 0.75            | 62.0        | 16.1        | 161            | 853.3          |
| 1.00            | 44.0        | 22.7        | 227            | 1203.1         |
| 1.25            | 37.0        | 27.0        | 270            | 1431.0         |
| 1.50            | 30.0        | 33.3        | 333            | 1764.9         |
| 1.75            | 26.8        | 37.3        | 373            | 1976.9         |
| 2.00            | 22.0        | 45.4        | 454            | 2406.2         |
| 2.25            | 20.0        | 50.0        | 50             | 2650.0         |

The first two columns of Table 1 are the \( V_{DC} \) voltage measurements and the period \( T \) of the alternating waves of the generator. The \( V_{DC} \) measurements were obtained by varying the supply voltage (\( V_a \)) of the DC motor; the next three columns are the calculated values: frequency (\( F \)), generator rotational speed (\( N_S \)) and \( N_D \). For the frequency the inverse of the period \( T \) was used, for \( N_S \) the equation (5) formula to obtain the speed of the generator in rpm where \( F \) is the frequency generated in Hertz, \( p \) is the number of pairs of poles and 60 are the seconds that equals one minute. Equation (2) was used to calculate \( N_D \).
2.1.1. Relationship between voltage ($V_{dc}$) and DC motor speed ($N_D$)

Figure 3 shows the graph of the $N_D$ and $V_{DC}$ points from table 1, estimating the linear trend equation (3) whose slope is the constant $C=1191.7$ rpm/V. It should be noted that the ideal is that it should not have the constant term (-32.557) but it must be considered that the measurements carried out also have a tolerance in their precision,

$$N_D = 1191.7 V_{DC} - 32.557$$  \hspace{1cm} (6)

![Figure 3. Relation between $N_D$ and $V_{DC}$.](image)

The armature resistance of the motor DC ($R_a$) was obtained as the average of the following measurements made with the rotor locked using the Fluke 175 multimeter in the resistance function: 49.5 Ω, 48.5 Ω, 48.3 Ω, 48.1 Ω, 48.1 Ω, then $R_a = 48.5$ Ω.

2.1.2. Obtaining $K_v$, $B$

To calculate the parameter $K_v$ (voltage constant (Vs / rad)) we are based on equation (9) therefore we need to calculate the counter electromotive force generated ($E_g$ (volt)) equation (8) where $V_a$ is the continuous supply voltage of the DC motor, $I_a$ its armature current and also calculate the angular velocity of the DC motor ($w_D$ (rad/s)) with equation (7) that transforms the rpm of $N_D$ into rad/s.

The first three columns of table 2 are the measured values $V_a$, $V_{DC}$, $I_a$ being $V_a$ the variable voltage on which the other two are based, the measurements were performed simultaneously with three Fluke 175 multimeters. The next 4 columns are the calculated values: $N_D$ with equation (6), $E_g$ with equation (8), $w_D$ with equation (7), $B$ the coefficient of viscous friction with equation (10).

$$w_D = \frac{N_D 2\pi}{60}$$ \hspace{1cm} (7)

$$E_g = V_a - I_a R_a$$ \hspace{1cm} (8)

$$K_v = \frac{E_g}{w_D}$$ \hspace{1cm} (9)

$$B = \frac{K_v I_a}{w_D}$$ \hspace{1cm} (10)
Table 2. Summary of measurements of $V_{DC}$, $I_a$ and calculations of $N_D$, $E_g$, $w_D$ and $B$ for values of $V_a$.

| $V_a$ | $V_{DC}$ | $I_a$ (mA) | $N_D$ | $E_g$ | $w$ (rad/s) | $B$ (Nms/rad) |
|------|---------|-----------|-------|------|------------|--------------|
| 4    | 0.657   | 39.0      | 750.0 | 2.10 | 78.54      | 11.57e-06    |
| 5    | 1.018   | 40.6      | 1180.5| 3.03 | 123.63     | 7.65e-06     |
| 6    | 1.425   | 41.6      | 1665.6| 3.98 | 174.42     | 5.65e-06     |
| 7    | 1.799   | 43.7      | 2111.3| 4.88 | 221.09     | 4.61e-06     |
| 8    | 2.100   | 45.0      | 2470.0| 5.81 | 258.65     | 4.05e-06     |
| 9    | 2.380   | 46.0      | 2803.6| 6.769| 293.60     | 3.65e-06     |
| 10   | 2.638   | 48.0      | 3111.1| 7.67 | 325.79     | 3.43e-06     |
| 11   | 2.810   | 50.4      | 3336.1| 8.55 | 349.35     | 3.38e-06     |

Figure 4 shows the graph of points $E_g$ and $w_D$ from table 2 estimating the linear trend equation (11) whose slope corresponds to the sought parameter $K_v = 0.0232 \text{Vs/rad}$, as in the previous case of the linear estimation. To obtain the parameter $C$, in this case the same thing also happens, that the appearance of the independent term (+0.0451) is due to the low precision in the measurements made with the three multimeters and it gives us to understand in the equation that with zero angular velocity a counter electromotive force is already being generated.

$$E_g = 0.0232w_D + 0.0451$$ (11)

To calculate the parameter $B$ we take the average value of its values given in the last column of table 2, resulting in $B = 5.49 \times 10^{-6} \text{Nms/rad}$.

2.1.3. Obtaining the armature inductance ($L_a$), moment of inertia ($J$) and torque constant ($k_t$).

To calculate the armature inductance of the DC motor ($L_a$) in Henries, we are based on equation (12), therefore it is required to measure the electrical time constant ($\tau_a$) of the coil $L_a$. For this case and with the rotor locked of the DC motor, it was applied to the input $V_a$ a step-type voltage of 4.48 volts and simultaneously measured with the oscilloscope at the ends of an external resistance of 56 $\Omega$ in series with the armature coil $L_a$. The time it took to reach 63% of the maximum voltage is the electrical time constant, its value being $\tau_a = 26 \mu s$. Finally, using equation (12) we calculate the inductance of the armature, resulting in $L_a = 2.717 \text{mH}$.

$$\tau_a = \frac{L_a}{R_a + R_{ext}}$$ (12)

$$J = B\tau_m$$ (13)

To calculate the moment of inertia ($J (\text{Nms}^2)$) we use equation (13) which calculates the moment of inertia as a function of the viscous friction coefficient $B$ and the mechanical time constant ($\tau_m$),
This constant is estimated as 1/3 of the time that elapses between disconnecting the motor power supply and stopping it, resulting in a value $\tau_m = 371.6$ ms.

For the torque constant (Kt (Nm/A)) its numerical value is the same as that of the voltage constant (Kv), then Kv = 0.0233 Nm/A.

2.2. DC motor model

In table 3 left column we have the equations for the DC motor model where $v_a(t)$, $i_a(t)$ are the field voltage and current, $T_M$ and $T_L$ the motor and load torque, $v_d(t)$, $i_d(t)$ are the armature voltage and current, in the right column are the Laplace transformations of the respective instantaneous equations.

| Table 3. DC motor equations: Instantaneous (a), Laplace (b). |
|----------------------------------------------------------|
| (a)                                                      | (b)                                      |
| $v_a(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} + e_g(t)$  | $e_g(t) = K_t w(t)$                      |
| $e_g(t) = K_v w(t)$                                      | $E_g(s) = K_t W(s)$                      |
| $v_F(t) = R_F i_F(t) + L_F \frac{di_F(t)}{dt}$           | $L_F s I_F(s) = v_F(s) - R_F I_F(s)$      |
| $T_M(t) = f \frac{dw(t)}{dt} + Bw(t) + T_L(t)$           | $J s W(s) = T_M(s) - BW(s)$              |
| $T_M(t) = K_T i_a(t)$                                    | $T_M(s) = K_T I_a(s)$                    |

Figure 5 represents the block diagram of the DC motor model obtained in Simulink, with an input $V_a$ as the armature supply voltage of the DC motor and the outputs $w(t)$ angular velocity, $i_a(t)$ armature current, theta position angle, TM motor torque.

To obtain the transfer function of the motor speed $W(s)$ with respect to the supply voltage $V_a(s)$ we carry out the following steps: from equation (23) we solve for $I_a(s)$, we take $E_g(s)$ from the equation (20), then in equation (24) we replace $I_a(s) E_g(s)$ obtaining equation (25):  

$$F(s) = \frac{W(s)}{V_a(s)} = \frac{K_t}{L_a s^2 + (L_a B + R_a) s + (K_t K_v + R_a B)}$$  (25)

From equation (22) we solve for TM(s) and replace in equation (24), then we solve for the transfer function $F(s) = \frac{W(s)}{V_a(s)}$ equation (25) and replace the parameters, obtaining the transfer function $F(s)$ of the speed of the DC motor with respect to $V_a(s)$ in terms of Laplace equation (26):

$$F(s) = \frac{W(s)}{V_a(s)} = 2.33 e^{-02}$$

$$F(s) = \frac{W(s)}{V_a(s)} = 5.543 e^{-09}s^2 + 9.895 e^{-05}s + 8.092 e^{-04}$$
Figure 5. Block diagram of the DC motor model

2.3. PID closed-loop DC motor control

The transfer function $F(s)$ of the DC motor equation (25) was used in the closed loop system with unity feedback gain for the controls P (proportional control), PI (proportional integral control), PD (proportional derivative control), PID (proportional, integral and derivative control), applying equation (27) (closed-loop transfer function).

Table 4 in the first column shows the gains of the P, PD PI and PID control blocks and in the right column the closed loop transfer functions that have been obtained for each type of PID control

$Y(s) = \frac{PID(s)F(s)}{1 + PID(s)F(s)}$ (27)

Table 4. PID (s) control equations and $Y(s) / X(s)$ closed loop transfer functions.

| PID(s)       | $Y(s)$                                      | $X(s)$                                      |
|--------------|---------------------------------------------|---------------------------------------------|
| P $K_p$      | $K_pK_t$                                    | $\frac{K_pK_t}{L_aJ_s^2 + (L_aB + R_d)s + K_tK_v + R_aB + K_pK_t}$ (32) |
| PD $K_p + sK_d$ | $\frac{(K_tK_d)s + K_pK_t}{L_aJ_s^2 + (L_aB + R_d + K_tK_v)s + (K_tK_v + R_aB + K_pK_v)s + K_tK_t}$ (33) |
| PI $K_p + \frac{K_i}{s}$ | $\frac{K_pK_s + K_tK_t}{L_aJ_s^3 + (L_aB + R_d)s + K_tK_v + R_aB + K_pK_v)s + K_tK_t}$ (34) |
| PID $K_p + sK_d + \frac{K_i}{s}$ | $\frac{(K_tK_d)s^2 + K_pK_s + K_tK_t}{L_aJ_s^3 + (L_aB + R_d + K_tK_v)s + (K_tK_v + R_aB + K_pK_v)s + K_tK_t}$ (35) |

In table 5 we apply the Routh–Hurwitz stability criterion for each of the PID controllers to obtain the gain of the controllers P ($K_p$ proportional gain) and PD ($K_p$ $K_d$ proportional and derivative gain).
Table 5. Application of the Routh-Hurwitz stability criterion for P and PD controls.

|     | P                   | PD                  |
|-----|---------------------|---------------------|
| $s^2$ | $L_aJ$              | $L_aJ$              |
| $s$  | $L_aB+R_dJ$         | $L_aB+R_dJ+K_tK_d$  |
| $s^0$| $K_tK_r+K_pK_r+R_dB$| $K_tK_r+K_pK_r+R_dB$|

$K_p > -\frac{R_dB}{K_r} - K_tK_v = -0.034$

$K_d > \frac{-L_aB - R_d}{K_t} = -4.247 \times 10^{-03}$

In Table 6 we apply the Routh-Hurwitz stability criterion for each of the PID controllers to obtain the gain of the PI controllers ($K_p$, $K_i$ gain proportional and integral) and PID ($K_p$, $K_i$, $K_d$ proportional, integral and derivative gain).

Table 6. Application of the Routh-Hurwitz stability criterion for PI and PID controls.

|     | PI                      | PID                      |
|-----|-------------------------|--------------------------|
| $s^3$ | $L_aJ$              | $L_aJ$              |
| $s^2$ | $L_aB+R_dJ$         | $L_aB+R_dJ+K_tK_d$  |
| $s$  | $K_tK_r+K_pK_r+R_dB$  | $K_tK_r+K_pK_r+R_dB$  |
| $s^0$| $K_tK_i$             | $K_tK_i$             |
|     | $K_i > 0$             | $K_p > -0.034$, $K_i > -0$, $K_d > -0.0042$ |

2.4. Modified PID control of closed loop DC motor

As mentioned in the introduction, the configuration in a PID can be slightly modified to improve its performance depending on the response to be obtained, as proposed by Eitelberg, who incorporated prior gain blocks to each controller, cited by [26].

They have added three gain blocks $F_p$, $F_i$ and $F_d$, these blocks do not modify the regulation properties of the system since the disturbance signal does not circulate through these blocks. What is affected is the closed-loop transfer function, which will not be the same as that established by the classic PID controller.

Equation (36) is the typical PID control where $u(t)$ is the control action, $e(t)$ the error signal, $K_p$ the proportional gain, $T_i$ the integral time, $T_d$ the derivative time.

$$u(t) = K_p \left[ e(t) + \frac{1}{T_i} \int_0^t e(t) dt + T_d \frac{de(t)}{dt} \right] \quad (36)$$

Figure 6. Modified PID controller block diagram.
Its transfer function in Laplace terms is given by equation (37), ordering as a fraction we have equation (38):

\[
PID(s) = K_p \left( \frac{1 + \frac{1}{T_i s} + T_d s}{T_i s} \right)
\]

(37)

\[
PID(s) = \frac{K_p(1 + T_i s + T_d T_i s^2)}{T_i s}
\]

(38)

Considering the PID (s) of equation (38), the closed-loop transfer function with modified PID control, of figure 6, is indicated in equation (39).

\[
\frac{Y(s)}{X(s)} = \frac{K_p(1 + F_p T_i s + F_d T_d T_i s^2)}{T_i s} \cdot \frac{F(s)}{1 + PID(s)F(s)}
\]

(39)

Table 7 shows the summary of the values that \(K_p\), \(K_i\) and \(K_d\) must take for the Routh-Hurwitz stability criterion to be fulfilled is shown.

| Control P | Control PD | Control PI | Control PID |
|-----------|------------|------------|-------------|
| \(K_p > -0.034\) | \(K_p > -0.0347\) \(K_d > -4.247 \times 10^{-3}\) | \(K_p > -0.034\) \(K_i > 0\) | \(K_p > -0.0347\) \(K_i > 0\) \(K_d > -0.0042\) |

Set of assumed values for the different gains according to the type of control and that meet the Routh-Hurwitz criterion

| \(K_p = 0.1\) | \(K_p = 0.2\) \(K_d = 0.2\) | \(K_p = 0.2\) \(K_i = 0.2\) | \(K_p = 1\) \(K_i = 1\) \(K_d = 1\) |
| \(K_p = 1\) | \(K_p = 0.2\) \(K_d = 1\) | \(K_p = 0.2\) \(K_i = 1\) | \(K_p = 0.2\) \(K_i = 1\) \(K_d = 0.2\) |
| | \(K_p = 1\) \(K_d = 1\) | \(K_p = 1\) \(K_i = 1\) | \(K_p = 0.2\) \(K_i = 1\) \(K_d = 1\) |

For the modified PID, the proportional gains \(K_p = 1\), \(K_i = 1\), \(K_d = 0\) were used. The values of the three gain blocks with value 1 reduce the structure to the classic PID, we will see the effect of only increasing the gain \(F_p\) in hundredths and thousandth in speed response, these values are shown in table 8.

| Table 8. Profit Block Values \(F_p\), \(F_i\) and \(F_d\) |
|-----------|-----------|-----------|
| \(F_p = 1\) | \(F_p = 1.03\) | \(F_p = 1.0305\) |
| \(F_d = 1\) | \(F_d = 1\) | \(F_d = 1\) |
| \(F_i = 1\) | \(F_i = 1\) | \(F_i = 1\) |

3. Results

Figures 7 and 8 are the results obtained for the proportional control in closed loop of the DC motor.
Figure 7. Proportional control response with $K_p = 0.2$.

Figures 9, 10 and 11 are the results obtained for the closed loop PD control of the DC motor for different values of $K_p$ and $K_d$.

Figure 9. Angular velocity response to proportional derivative control for $K_p$, $K_d$ respectively (0.2,0.2) (1,1)

Figure 10. Angular velocity response to proportional derivative for $K_p$, $K_d$ respectively (0.2,1) (1,1)

Figure 11. Angular velocity response to the proportional derivative control for $K_p$, $K_d$ respectively (0.2,1) (1,1).

Figures 12 and 13 are the results obtained for the closed loop PI control of the DC motor.
Figure 12. Response to the Proportional integral control for $K_p, K_i$ respectively (0.2,0.2) (1,1).

Figure 13. Response to the Proportional integral control for $K_p, K_i$ respectively (0.2) (1,1).

Figures 14 and 15 are the results obtained for the proportional integral derivative control in closed loop of the DC motor.

Figure 14. Response of the PID control for values of $K_p, K_i, K_d$ respectively (0.2,0.2,0.2) (1,1,1).

Figure 15. Response of the PID control for values of $K_p, K_i, K_d$ respectively (0.2,1,1) (1,1,1).

Figure 16 are results obtained for the modified closed-loop PID control of the DC motor.

Figure 16. Response of the modified PID control for the values of $F_p, F_i, F_d$ respectively (1.0306,1,1) (1.03,1,1) (1,1,1).
Table 9. PID control results.

| Control P | Control PI | Control PD | Control PID |
|-----------|------------|------------|-------------|
| Kp | tresp | W_estac | Kp | tresp | W_estac | W_pico | Kp | Ki | Kd | tresp | W_estac | W_pico |
| 0.2 | 82 ms | 0.843 | 0.2 | 5.77 s | 1 | 0.2 | 0.2 | 1 ms | 0.976 | 0 | 0.2 | 0.2 | 0.2 | 6.5s | 1 | 1.01 |
| 1 | 19 ms | 0.966 | 0.2 | 1 | 1.28 s | 1 | 0.2 | 1 | 6 s | 0.872 | 1.21 | 1 | 1 | 1 | 7.09s | 1 | 1.21 |
| 1.0306 | 22 ms | 0.936 | 1 | 1 | 3.65 s | 1 | 1 | 1 | 1 | 0.995 | 1.21 | 0.2 | 1 | 1 | - | - | 1.02 |

Table 10. Modified PID control results.

| Modified PID control | F_p | F_i | F_d | K_p | K_i | K_d | tresp | W_estac | W_pico |
|----------------------|-----|-----|-----|-----|-----|-----|-------|--------|--------|
| 1.0306               | 1   | 1   | 1   | 1   | 0   | 0   | 0     | 1      | 0      |
| 1.03                 | 1   | 1   | 1   | 1   | 0   | 3.31 s | 1     | 0      |        |
| 1                    | 1   | 1   | 1   | 1   | 1   | 7.1 s | 1     | 0      |        |

4. Conclusions

The mathematical model of the DC motor characterized by the parameters $K_v$, $K_i$, $B$, $L_a$, $R_a$, $J$ was obtained by measuring the armature voltage and current, which allowed establishing a closed-loop control system for a modified PID. With the Routh-Hurwitz criterion, it was possible to calculate the control parameters $K_p$, $K_i$, $K_d$ that allowed, in a first phase, an optimal stability and rejection of disturbances in classic P, PI, PD, PID controllers elaborated by means of a block diagram in closed loop using MatLab / Simulink, table 9 shows a summary of the angular velocity response time. In a second phase, a modified PID controller was used taking into account Eitelberg's proposal, considering the calculated control parameters $K_p$, $K_i$, $K_d$ and assigning a value equal to one to the gain blocks $F_i$ and $F_d$, so that the $F_p$ gain generates the changes in the transient response to reference variations, this was achieved by modeling in Matlab / Simulink assigning a value of 1.0306 to the $F_p$ block, with which the modified PID controller in closed loop offered a zero speed response time (0) with stable output, which was higher than that offered by the P, PI, PD, PID controllers, these results are shown in table 10.

5. Reference

[1] Zayas I. 2018 El desarrollo tecnológico y la innovación como ente principal de competitividad en las empresas del sector agropecuario en el municipio de angostura, Sinaloa. Revista Mexicana de Agronegocios, vol. 42, pp. 867-877, Sociedad Mexicana de Administración Agropecuaria A.C. Universidad Politécnica del Valle del Évora, México. https://www.redalyc.org/articulo.oa?id=14156175006

[2] Espinoza M 2017 Plataforma para evaluar el desempeño energético de controladores PID en motores de corriente directa basada en la norma ISO 50001. Tesis para obtener el grado de maestro en ciencias en energías renovables. Centro de investigación en Materiales Avanzados S.C. (CIMAV). Maestría en Energías Renovables Área eficiencia energética. Pag 6 https://acortar.link/Z6mOCf

[3] Tejada G, Cruz J, Uribe Y and Ríos J 2019 Innovación tecnológica: Reflexiones teóricas (Technological innovation: Theoretical reflections) en inglés. Revista Venezolana de Gerencia, vol. 24, núm. 85, 2019 Universidad del Zulia

[4] Valenzuela J 2013. Manual de tipos de motores eléctricos, reconocimiento y sus aplicaciones en la industria. Tesis, escuela politécnica nacional Quito ecuador. https://bibdigital.epn.edu.ec/bitstream/15000/6069/1/CD-4796.pdf

[5] Aranda R 2018. Control de motores de corriente continua con compensación de zona muerta. Tesis. Escuela Superior de Ingeniería, Universidad de Almería. Pag 10 https://acortar.link/kdfNQ4

[6] Nasimba and Nasimba J 2018. Análisis de la eficiencia y características del par en función de la velocidad de un motor de corriente continua (c-d) con el campo en derivación. Revista Publicando, 5 (18), 2018, 112-132. ISSN 1390-9304 112 https://dialnet.unirioja.es/servlet/articulo?codigo=7149483
[7] Comité español de automática-CEA 2009 Libro Blanco del control automático 1ª edición 2009, ISBN: 978-84-692-5966-5 p.44, https://acortar.link/LOSPKM

[8] López O 2018 La eficiencia energética en la industria: una solución efectiva para ahorrar energía. Letras ConCiencia Tecnológica, 31-38. Recuperado a partir de https://revistas.itc.edu.co/index.php/letras/article/view/120

[9] Hernández V, Silva R and Carrillo R. 2013 Control automático. Teoría de diseño, construcción de prototipos, modelado, identificación y pruebas experimentales. Colección CIDETEC del Instituto Politécnico Nacional. México, DF, México. ISBN: 978-607-414-362-1. https://acortar.link/AHDCwP

[10] Walaa M, Elsrogy M, Fkirin M and Hassan M 2013 Speed control of DC motor using PID controller based on artificial intelligence techniques. DOI: 10.1109/CoDIT.2013.6689543

[11] Vergara A; Salazar E; Ramiro J and Ramiro J 2017 Control de velocidad PI a un motor de DC utilizando herramientas Open Source, https://acortar.link/9Qen1N

[12] Control de velocidad de un motor de CD basado en mediciones de la corriente de armadura, Ingeniería, investigación y tecnología, vol. XIX, núm. 4, e039, 2018 Facultad de Ingeniería, UNAM https://acortar.link/9Qen1N

[13] Abad D 2017. Evaluación del desempeño de los controladores PID aplicados al control de velocidad y tensión del grupo turbinia-generador de la Central Hidroeléctrica Alazán de 6.23MW y elaboración de una propuesta de mejoramiento basada en el diseño de un controlador predictivo basado en modelo. Universidad Politécnica Salesiana, Cuenca – Ecuador, 2017 Maestría en Control y Automatización Industriales de la Universidad Politécnica Salesiana. Printed in ecuador. https://acortar.link/yN5x5M

[14] Huba M; Chamraz S; Bistak P; Vrancic D 2021 Making the PI and PID Controller Tuning Inspired by Ziegler and Nichols Precise and Reliable. Sensors 2021, 21, 6157 https://doi.org/10.3390/s21186157

[15] Naregalkar S 2017 Online Auto Selection of Tuning Methods and Auto Tuning PI Controller in FOPDT Real Time Process-pH Neutralization,Energy Proced. https://acortar.link/Wc9LFf

[16] Hernández C 2015 Revista de Tecnología e Innovación, Septiembre Vol.2 No.4 688-700 (Articulo) https://acortar.link/r7fVsw

[17] Kuo C 2016 Sistemas de Control Automático. 7ma. Edición. Prentice-Hall Hispamericana, S.A. México. ISBN 968-880-723-0. Pag. 696-697. https://acortar.link/qYUqqz

[18] Martínez U; Marcelo B; Muñoz B and Hernández J 2019 Control PID Convencional con Filtro Pasa Bajas para el Control de Velocidad de un Motor de CD, VOL 5, 16-19, ISSN: 2448-6817, http://200.79.179.163/reia/descargables/2019/16-19.pdf

[19] Carrillo A 2011. Sistemas Automáticos de Control Fundamentos Básicos de Análisis y Modelado. Universidad Nacional Experimental “Rafael María Baralt” (UNERMB). Fondo Editorial UNERMB Colección un Profesor, un libro. 2da. edición. ISBN: 978-980-6792-12-8.

[20] Barcia R, Barrones E, Romero J and Miguel O. (2019). Sintonización de Controladores PID para Control de Velocidad de Motores de Corriente Continua mediante Algoritmos Genéticos: Array. Revista Perspectivas, 1(2), 31–37 https://acortar.link/pHXKL5

[21] Tapías L (2018). Tesis. Diseño e Implementación de un vehiculo uniaxial con control de balanceo. Universitat Politecnica de Cataluña Barcelona TECH. https://acortar.link/yWAhss

[22] Colman A (2020). Tesis. Propuesta de implementación de un sistema de control en lazo cerrado para banco didáctico de hidráulica transparente. Universidad Técnica Federico Santa María – Sede Viña del Mar- José Miguel Carrera. https://acortar.link/BimvQ

[23] Borja P 2019 Tesis. Implementación de maqueta de motor DC y aplicación de diferentes tipos de control utilizando Arduino. Universidad del País Vasco Pag 11-12, 17-25 https://acortar.link/Y2J9VY

[24] Gil J y Díaz A 2009 Fundamentos de Control Automático de Sistemas Continuos y Muestreado.: Editorial Unicopia, C.B. España ISBN 978-84-613-4618-9 https://core.ac.uk/download/pdf/83559623.pdf
[25] Sabogal O 2016 Diseño, construcción y validación de un sistema de control de posición autosintonizable para un cilindro neumático de doble efecto. Universidad Tecnológica de Pereira. Facultad de Ingeniería Mecánica Maestría En Sistemas Automáticos De Producción Pereira pag. 80-84. https://acortar.link/hXbmsF

[26] Tacconi E, Mantz R, Solson J and Puleston P 2005. Controladores basados en estrategia PID. LEICI, Facultad de Ingeniería, UNLP Pag 19 https://catedra.ing.unlp.edu.ar/electrotecnia/cys/pdf/apunte_pid.pdf

[27] Degem Systems Manual curso EB-109. Pag11, http://www.ditech.gr/pdf/eb.pdf