

## A DIDACTIC SPEED CONTROL SYSTEM OF DC MOTORS BASED ON DATA ACQUISITION SYSTEM

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**Abstract.** This paper presents the development of speed control for DC motors based on data acquisition systems. The work shows the development of experiments for power electronics laboratory to engineering courses. The experiences include mathematical modeling of the DC motor using the method of weighted least squares and design of digital PI controllers with anti-windup and limitation of armature current. The driving is conducted through full-bridge driver with IGBT. The control of the applied voltage at IGBT is developed by PWM algorithm. The approach shows the association between the simulation and practical results.

**Keywords:** education, power electronics, PI control system, motor drive, modeling of control systems

### 1. INTRODUCTION

In industry there are many cases in which the speed control of motors is desirable. These include, for example, applications on pulp and paper industries, processes of rolling of aluminum or steel, on vehicle traction such as electrical trains or subway, driving for auto guided vehicles (AGV's), and control of DC servomotors in the automotive industry. Usually the design of these systems involves complex structures, sophisticated equipment and high cost. Furthermore, most of the solutions available on the market are limited and no versatile, that difficult the introduction of new technologies for improving performance.

This work presents a solution for speed control of DC motor. This problem has been widely studied in research work aiming the developing new technologies, the controlled motor drive and the deployment of digital control systems (Mohan, *et al.*, 2003), (Patané, 2009), (Sousa and Bose, 1994). However, the main contribution of this work is development of practical experiments for teaching the concepts of control system and power electronic applied to drive DC motors. The paper describes the following experiments: development of a didactic data acquisition system (Li and Khan, 2005) for driving DC motors; parameters estimation a DC motor based on weight least squares method (Isermann, 1992); design, simulation and practical implementation of speed control using PI controllers.

### 2. MODELING OF DC MOTORS

The open loop speed control system of a separately-excited DC motor can be represented by the block diagram illustrated at Fig. 1, where  $L_a$  is the inductance of armature winding,  $R_a$  is the resistance of armature winding,  $J$  is the inertia of motor, load, shaft and couplings,  $B$  is the viscous friction between motor and load,  $k_t$  is the constant of torque and  $k_\omega$  is the constant of speed (Patané, 2009).

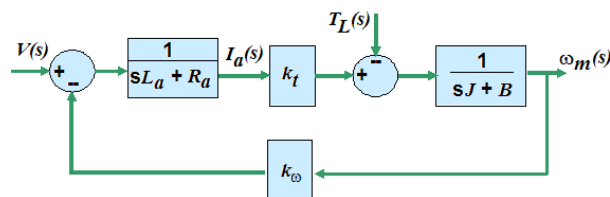


Figure 1. Block diagram of DC motor with separately-excited field

Some variables of the system are the speed of motor ( $\omega_m(s)$ ), the armature current ( $I_a(s)$ ), the voltage applied on motor ( $V(s)$ ) and the load coupled on motor shaft ( $T_L(s)$ ). Assuming  $T_L(s) = 0$ , we get the following transfer function:

$$\frac{\omega_m(s)}{V(s)} = \frac{k_t}{(sL_a + R_a)(sJ + B) + k_t k_\omega} \quad (1)$$

The measuring of the speed is obtained using a tachogenerator that converts the motor speed (rpm) to voltage output ( $V_{tacho}(s)$ ) as illustrated at Fig. 2. A Hall-Effect sensor allows measure the current on winding armature getting the voltage output ( $V_{hall}(s)$ ). The control of the voltage applied on motor was done by a data acquisition system that produces the control voltage ( $V_C(s)$ ). A PWM signal with a pulse width proportional to control voltage is produced by software and sent to full-bridge circuit resulting on the desired voltage applied on motor ( $V(s)$ ). At Fig. 2  $k_{tacho}$  is the gain of tachogenerator,  $k_{FB}$  is the gain of full-bridge circuit,  $k_{PWM}$  is the gain of algorithm PWM and  $k_{hall}$  is the gain of current sensor. On modeling of system, that includes the algorithm for PWM generation and the electronic circuit used for drive the DC motor, for simplicity, were neglected the constants of time.

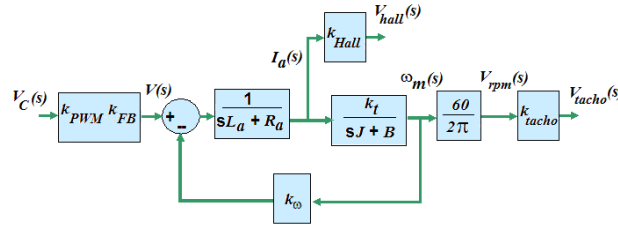


Figure 2. Block diagram of DC motor with separately-excited field including a full-bridge and current and speed sensors

To simplify the model were not considered the delay of response at the sensors, data acquisition system and electronic circuit for driving, resulting in the following transfer functions that relate the current and the speed of motor with the voltage produced by data acquisition board.

$$\frac{V_{tacho}(s)}{V_C(s)} = \frac{60k_t k_{tacho} k_{FB} k_{PWM}}{2\pi L_a J} \frac{1}{s^2 + \left(\frac{R_a}{L_a} + \frac{B}{J}\right)s + \left(\frac{R_a B}{L_a J} + \frac{k_t k_\omega}{L_a J}\right)} \quad (2)$$

$$\frac{V_{hall}(s)}{V_C(s)} = \frac{k_{hall} k_{FB} k_{PWM} \left(s + \frac{B}{J}\right)}{L_a} \frac{1}{s^2 + \left(\frac{R_a}{L_a} + \frac{B}{J}\right)s + \left(\frac{R_a B}{L_a J} + \frac{k_t k_\omega}{L_a J}\right)} \quad (3)$$

Using Fig. 2, we can deduce:

$$V_{tacho}(s) = \frac{60k_t k_{tacho}}{2\pi(sJ + B)} I_a(s) \quad (4)$$

Adjusting the Eq. 4 and getting the Inverse of Laplace Transform considering initial conditions as zero, is obtained the following state space equation:

$$\dot{v}_{tacho}(t) = -\frac{B}{J} v_{tacho}(t) + \frac{60k_t k_{tacho}}{2\pi J} i_a(t) \quad (5)$$

Also using Fig. 2, we can verify:

$$V_{hall}(s) = \frac{k_{hall} k_{PWM} k_{FB}}{(sL_a + R_a)} V_C(s) - \frac{2\pi k_{hall} k_\omega}{60k_{tacho} (sL_a + R_a)} V_{tacho}(s) \quad (6)$$

Adjusting the Eq.6 and getting the Inverse of Laplace Transform considering initial conditions as zero, is obtained the following state space equation:

$$\dot{v}_{hall}(t) = \begin{bmatrix} -R_a \\ L_a \end{bmatrix} v_{hall}(t) + \begin{bmatrix} k_{hall}k_{PWM}k_{FB} & -\frac{2\pi k_{hall}k_{\omega}}{60k_{tacho}L_a} \end{bmatrix} \begin{bmatrix} v_C(t) \\ v_{tacho}(t) \end{bmatrix} \quad (7)$$

The equivalent discrete equations for Eq. 5 and Eq. 7, including zero-order hold are (Patané, 2009):

$$v_{tacho}(k+1) = e^{-\frac{B_T}{J}} v_{tacho}(k) + \left(1 - e^{-\frac{B_T}{J}}\right) \left(\frac{60k_t k_{tacho}}{2\pi B}\right) i_a(k) \quad (8)$$

$$v_{hall}(k+1) = e^{-\frac{R_a T}{L_a}} v_{hall}(k) - \frac{k_{hall}k_{PWM}k_{FB}}{R_a} \left(e^{-\frac{R_a T}{L_a}} - 1\right) v_C(k) + \frac{2\pi k_{hall}k_{\omega}}{60k_{tacho}R_a} \left(e^{-\frac{R_a T}{L_a}} - 1\right) v_{tacho}(k) \quad (9)$$

### 3. HARDWARE

Figure 3 presents the complete control system used at practical experiments developed for teaching in electrical and mechatronics engineering courses. The system is constituted by the following components:

- DC motor with its speed controlled;
- DC generator, coupled to DC motor, which feeds a bank of impedances and acts as variable charge for the system;
- full-bridge driver with IGBTs;
- speed sensor (tachogenerator);
- current sensor (Hall-Effect sensor);
- data acquisition system.

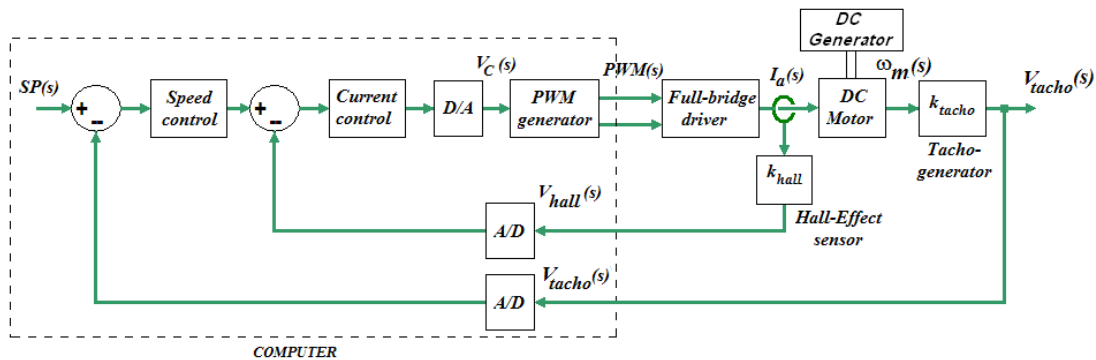


Figure 3. Block diagram of speed control system with limitation of armature current

The DC motor used, illustrated at Fig. 4 has rated speed of 1800 rpm, rated voltage of 200 VDC, nominal current of 11.5 A and power of 2kW. The gains of full-bridge circuit and PWM algorithm are  $k_{PWM} = 5$  and  $k_{FB} = 120/5$  V/V.

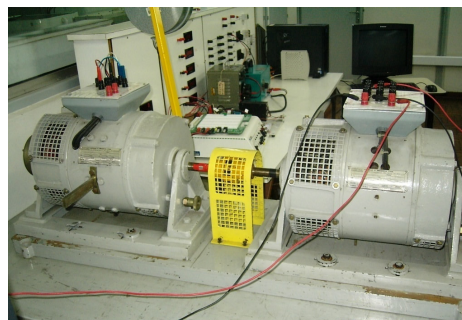


Figure 4. DC motor and DC generator coupled

The tachogenerator consists of a DC generator coupled to the shaft of motor that acts as speed sensor providing the value of the voltage proportional to the speed. The proportional relationship is approximately  $k_{\text{tach}} = (1/185) \text{ V/rpm}$ .

When starting the motor, the current rises to several times the rated current of the machine. The high electrical current could cause serious problems to the machine or to the electronic components of the circuit driver. Therefore, a closed loop current control was developed for limit it, thus avoiding damage the system.

For the implementation of the current control was used the Hall sensor CSLA1CD, which allows measurement of AC or DC currents from 0 to 57 A, has response time of 3 ms, uses power source (VCC) from 8 V to 12 V and shows a sensitivity of  $k_{\text{hall}} = 49.6 \text{ mV / A}$ .

In order to implement the control computationally were used the educational kit ELVIS™ (Educational Laboratory Virtual Instrumentation Suite) and a software package that allows to obtain, to analyze and to display the data obtained in the acquisition. This kit, illustrated at Fig. 5, is constituted of a data acquisition board (DAQ) programmable by software based on LabVIEW™, a multifunctional device and a workstation with protoboard designed for to develop the applications (Li and Khan, 2005). The data acquisition board NI PCI-6251, available on the kit, has eight channels of differential analog inputs (or 16 single-end) with A/D converter of 16 bits and sampling rate of 1.25 MS/s to 1 MS/s with configurable range  $\pm 10 \text{ V}$ ,  $\pm 5 \text{ V}$ ,  $\pm 2 \text{ V}$ ,  $\pm 1 \text{ V}$ ,  $0.5 \text{ V}$ ,  $\pm 0.2 \text{ V}$  or  $\pm 0.1 \text{ V}$ . It also has two channels of analog output with D/A converter of 16 bits and sampling rate of 2.86 MS/s to 2 MS/s with configurable ranges  $\pm 10 \text{ V}$  or  $\pm 5 \text{ V}$ .

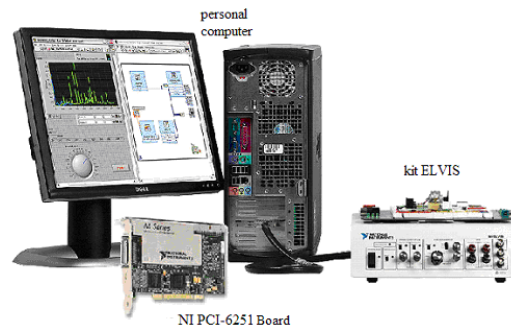


Figure 5. Data acquisition system with NI PCI-6251 board

Using the platform described above is possible to prepare the following practical experiments for teaching control systems and DC motor drive in engineering course:

- development of a didactic data acquisition system for driving DC motors;
- parameters estimation of a DC motor based on weight least squares method;
- design, simulation and practical implementation of speed control using PI controllers.

These experiments were performed in laboratory and the methodology adopted as well the results obtained are presented in details below.

#### 4. A DIDACTIC DATA ACQUISITION SYSTEM

This experiment aims to make the students to understand how to use the graphical interface software used for the development of a didactic data acquisition system.

First of all, the student must to learn to configure a lot of functions available at the software, as for example:

- simulation tools applied on control systems;
- design of filters (low-pass, high-pass and band-pass filters);
- generation of a PWM control signal;
- analysis of the frequency spectrum;
- using of Boolean variables, case structures, mathematical operations, among others.

In a second part of experience, the student develops, step by step, a data acquisition algorithm, that can be easily constructed using a wizard. The program developed allows measuring a signal sent by a sensor by mean of an analog input, and transmits a standard signal by analog output.

Finally, after this, the student is able to understand the algorithm developed in LabVIEW™ for the specific application (Patané, 2009) that includes the following functions:

- settings for analog inputs and outputs;
- settings for sampling time, simulation time, startup and shutdown (run / stop);
- speed and current control system, anti-windup controller and filters;
- PWM algorithm;
- user interface including digital controls for setpoint, display of signals from sensors, display graphics, etc.

The PWM algorithm uses a saw-tooth signal with frequency of 1kHz to produce the signal, whose amplitude is 5V. The signals PWM0 and PWM1 are produced by control algorithm on analog output from the data acquisition board.

The program also includes algorithm for edge detecting and protection to prevent the two sides of the bridge are triggered simultaneously. A delay of response is introduced when reversing the polarity of the signal control, resulting in reversal of electrical current direction, controlled by the selection between outputs PWM0 or PWM1.

Figure 6 shows the full-bridge circuit used for drive the motor that presents the following components:

- 4 IGBT's forming a H-bridge transistorized;
- integrated circuit IR2110 that allows to drive two independents IGBTs, one with floating emitter and another with emitter connected to ground; this circuit includes opto-coupler, drive circuit with MOSFETs and a *bootstrap* capacitor;
- a network formed by resistance and diode, connected to the gate of MOSFETs in order to reduce the reverse peak of current and produce a delay on drive cycle without affecting the power off.

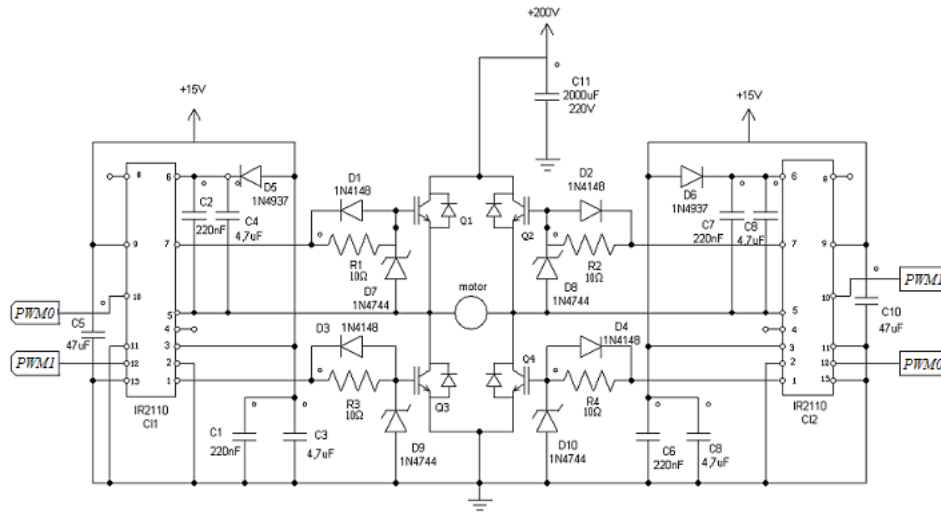


Figure 6. Full-bridge circuit with IGBTs and integrated circuit IR2110

## 5. PARAMETERS ESTIMATION

This experiment aims to estimate the parameters of DC motor. For this, the students perform tests with the system in open loop using the data acquisition system. Working with the data of voltage and current measured after the application of a step in input voltage, an algorithm based on the weight least squares method is then applied to determine the parameters of system.

The algorithm allows determine the parameters on Eq. 8 and Eq. 9, which can be defined as:

$$\theta_1 = \left[ e^{-\frac{B}{J}T} \left( 1 - e^{-\frac{B}{J}T} \right) \left( \frac{60k_t k_{tacho}}{2\pi B} \right) \right] \quad (10)$$

$$\theta_2 = \left[ e^{-\frac{R_a T}{L_a}} - \frac{k_{hall} k_{PWM} k_{FB}}{R_a} \left( e^{-\frac{R_a T}{L_a}} - 1 \right) \frac{2\pi k_{hall} k_{\omega}}{60k_{tacho} R_a} \left( e^{-\frac{R_a T}{L_a}} - 1 \right) \right] \quad (11)$$

So, the Eq. 8 and Eq. 9 can be rewritten as:

$$Y_i(k+1) = \theta_i U_i(k) \quad \text{for } i = 1,2 \quad (12)$$

Where:  $U_1(k) = [v_{tacho}(k) \quad i_a(k)]^T$ ;  $U_2(k) = [v_{hall}(k) \quad v_c(k) \quad v_{tacho}(k)]^T$ ;  $Y_1(k+1) = v_{tacho}(k+1)$  and  $Y_2(k+1) = v_{hall}(k+1)$ .

For estimate the parameters  $\theta_1$  e  $\theta_2$  of the model, initially was performed the data acquisition of voltage and current after the application of a step in input voltage (setpoint – SP).

Figure 7 shows the electrical current measured by Hall sensor and the voltage measured by tachogenerator. Figure 8 shows, in zoom, the electrical current which is a pulsed signal with frequency around 9.5 Hz. An algorithm was developed using MATLAB™ for obtain the average values of electrical current during certain limited periods of time.

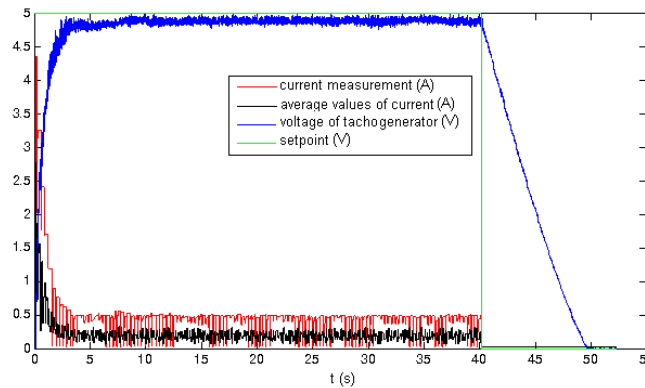


Figure 7. The speed and electrical current of motor measured after a step input applied on system

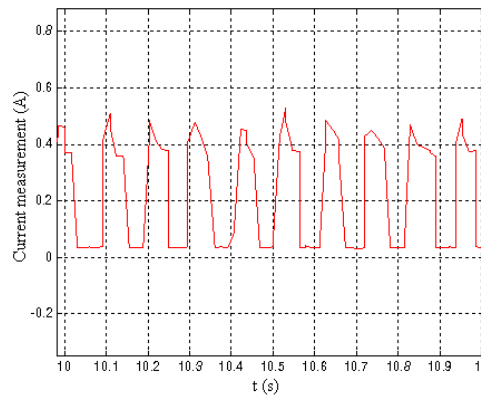


Figure 8. Current signal measured, in zoom

The algorithm based on weighted least square method (Isermann, 1992), used for estimation of parameters, can be summarized as follows:

1. Choose a weighting diagonal matrix  $P_i(k)$  with order  $n \times n$ , where  $n$  is the number of variables on the state space representation, such that the random terms of the main diagonal are equal and relatively high.

2. Setting a value to variable forgetting  $\gamma$  and to auxiliary variable  $\alpha$ , such that:  $0 < \gamma_i \leq 1$  and  $\alpha_i = 1 - \gamma_i$ . The parameter  $\gamma$  provide a capacity of different weighting to the observations, giving greater importance to the latest measures, once they contains most updated information and need have great influence.

3. Initialize  $Y_i(k+1)$ ,  $Y_i(k)$  and  $U_i(k)$  from the input and output values collected by the data acquisition system.

4. Assume initial values, random and different, for the estimated values  $\hat{\theta}_i(k+1)$  and  $\hat{\theta}_i(k)$ .

Repeat the operations listed as 5 to 9 while the tolerance for error  $\epsilon$  in estimation satisfies the condition  $\max|\hat{\theta}_i(k+1) - \hat{\theta}_i(k)| \geq \epsilon$ .

5. Update the values  $\hat{\theta}_i(k) = \hat{\theta}_i(k+1)$ .

6. Calculate the Kalman gain by assuming :

$$K_i(k) = \frac{P_i(k)}{\gamma_i} U_i(k) \left( \frac{1}{\alpha_i} + U_i^T(k) \frac{P_i(k)}{\gamma_i} U_i(k) \right)^{-1}$$

7. Estimate the new value  $\hat{\theta}_i(k+1)$  by:

$$\hat{\theta}_i(k+1) = \hat{\theta}_i(k) + K_i(k) (Y_i(k) - U_i^T(k) \hat{\theta}_i(k))$$

8. Calculate the new weighting diagonal matrix by:

$$P_i(k) = \frac{1}{\gamma_i} (1 - K_i(k) U_i^T(k)) P_i(k)$$

9. Update:  $Y_i(k) = Y_i(k+1)$ ;  $U_i(k) = U_i(k+1)$ .

The convergence of the parameters  $\theta_1$  and  $\theta_2$  has been analyzed using two algorithms separately. Figure 9 shows the convergence of  $\theta_1$  after use the algorithm where the diagonal matrix  $P_1(k)$  is (2x2) with terms equal to  $10^8$ ,  $\gamma_1=0.99$  and  $\alpha_1=0.01$ . The accuracy achieved was equal to  $10^{-6}$  after 439 iterations. Figure 10 shows the convergence of  $\theta_2$  after use the algorithm where  $P_2(k)$  (3x3) has terms equal to  $10^9$ ,  $\gamma_2=0.95$  and  $\alpha_2=0.05$ . The accuracy achieved was equal to  $10^{-4}$  after 172 iterations.

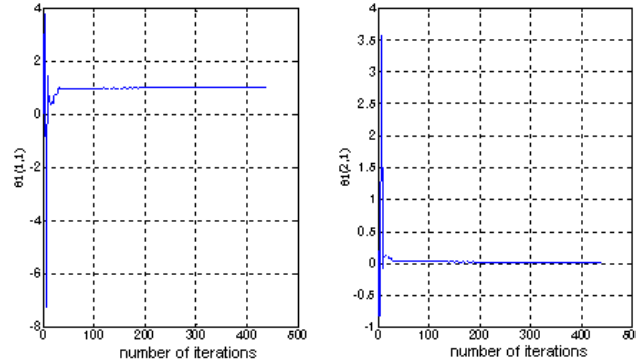


Figure 9. Convergence of parameters in  $\theta_1$

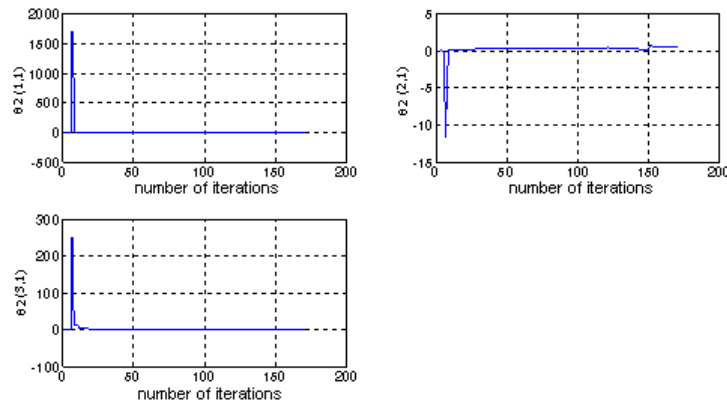


Figure 10. Convergence of parameters in  $\theta_2$

Substituting the estimated values  $\theta_1$  and  $\theta_2$  at Eq. 10 and Eq. 11 were defined the parameters of the system resulting the following:  $R_a = 6.3464 \Omega$ ,  $L_a = 136,884 \text{ mH}$ ,  $k = 0,834074 \text{ N.m/A}$ ,  $k_\omega = 0.834074 \text{ V/rpm}$ ,  $B = 8,812141 \times 10^{-3} \text{ N.m.s/rad}$  and  $J = 38,6667 \times 10^{-3} \text{ Kg.m}^2$ . The estimated parameters were substituted on models at Eq. 2 and Eq. 3 and simulated using MATLAB<sup>TM</sup>, getting the graphics presented in Fig. 11 and Fig. 12 which show the comparison between the practical results obtained by data acquisition and simulated using the estimated parameters. The similar behavior in the graphs validates the modeling performed experimentally.

## 6. PI CONTROLLERS

This experiment shows the design, simulation and practical implementation of the speed control using PI controllers. It was used Proportional Integral (PI) controller instead of Proportional (P) or Proportional Integral and Derivative (PID) controllers because the integral component allows cancelling the stationary error, while the derivative component could produce high current or voltage peaks in driver electronic circuit.

The DC motor is driven using configuration with independent excitation and its speed is controlled by the armature voltage provided by the algorithm generated in the LabVIEW<sup>TM</sup> software. The algorithm compares the signal of speed from tachogenerator with the desired value (setpoint) which is selected by the user on front panel of the program as illustrated at Fig. 6. This comparison defines if it is necessary accelerate or brake the DC motor. So, the algorithm defines the suitable PWM signal: PWM0 or PWM1.

The controllers used for speed and current control ( $PI_s$  and  $PI_c$ ) can be represented by:

$$PI_s(s) = k_s \frac{(s + 1/T_s)}{s} \quad (13)$$

$$PI_c(s) = k_c \frac{(s + 1/T_c)}{s} \quad (14)$$



Where  $k_s$  and  $k_c$  are the gain of controllers on speed and current loops, and  $T_s$  and  $T_c$  are the corresponding time constants. The resulting complete control system is illustrated at Fig. 13 where  $SP(s)$  defines the speed desired (setpoint) and  $V_{IaSP}(s)$  is the reference to loop of current control.

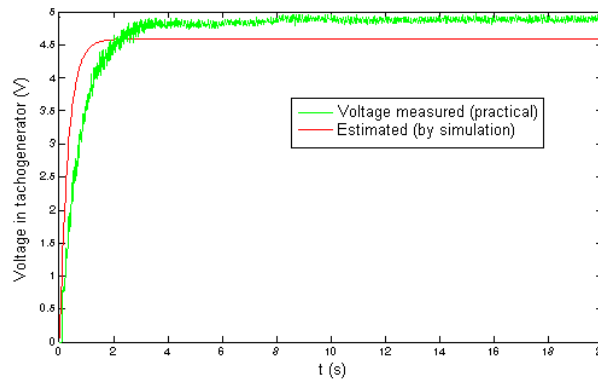


Figure 11. Voltage in tachogenerator measured on open loop speed control system – practical and simulation

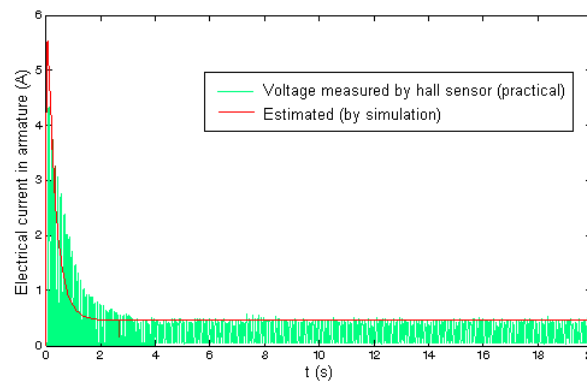


Figure 12. Electrical current in armature measured on open loop speed control system – practical and simulation

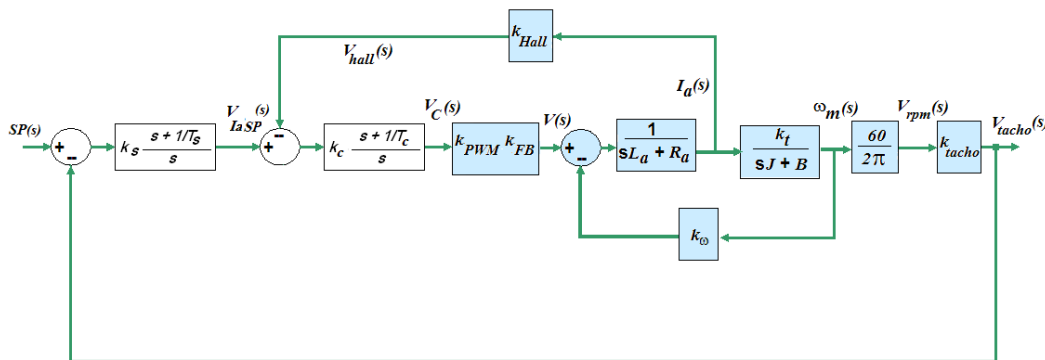


Figure 13. Block diagram of the complete control system

Substituting all the values obtained by modeling the system results the transfer function on current control loop (Eq. 3) with poles -3.2786 and -43.3126. To tune the PI current controller for limitation of the electrical current, was adopted the method of cancellation of the more instable pole of the system, resulting on  $T_c = 0,305$  s. The gain was adjusted by trial and error, choosing the best gain by simulation. Figure 14(a) shows the step response with gains  $k_c = 0.02$ ,  $k_c = 0.1$ ,  $k_c = 1$  and in open loop. We chose to use the gain  $k_c = 0.02$  to avoid rapid increase in the current of motor because, as it was observed during the experimental tests, the peak current could damage to drive circuit.

After tuned the current controller, the next step is tune the controller on loop of speed control. For this, using the  $PI_c(s)$  and after simplifying we get the block diagram illustrated at Fig. 15. Either, to tune the PI speed controller it was adopted the method of cancellation of the more instable pole of the system, resulting on  $T_s = 266.667$  s.



Simulating the system with  $PI_c(s)$  and  $PI_s(s)$  where the gain  $k_s$  was adjusted to achieve a compromise between speed of response (higher gain) and lower oscillation (reduced gain) as illustrated at Fig. 14(b). The gain chosen were  $k_p = 100$  because it allows efficient control without large increases in voltage or current produced.

Based on the project, tests were performed with data acquisition and by simulation. At these tests were considered a lot of practical aspects will be detailed below.

The electrical current measured by Hall sensor and the voltage measured by tachogenerator present considerable noise level. To minimize this noise were used low-pass filters, both given by:

$$G_f(s) = \frac{200}{s + 200} \tag{15}$$

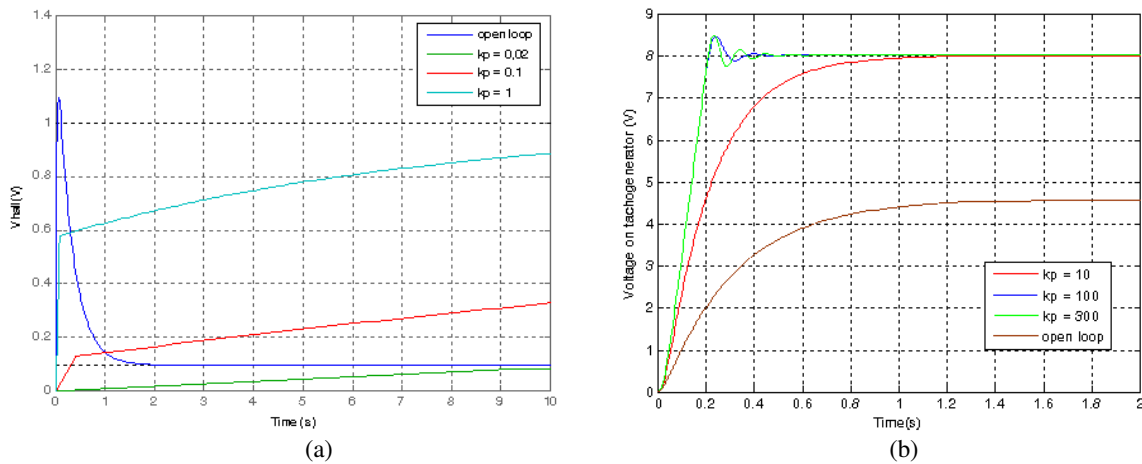


Figure 14. Simulation of closed loop current control using PI controller with gain adjusted  
(a) Current control (b) Speed control

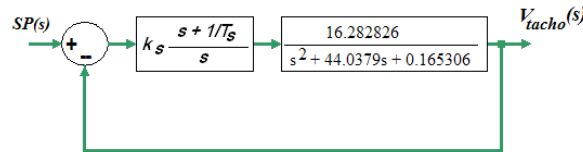


Figure 15. Block diagram of the speed control loop

The analog output from data acquisition system presents voltage limited to  $\pm 10$  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 on current and speed loop the control algorithm includes an anti-windup control method as illustrated at Fig. 16. The strategy is basically to eliminate the effect of integration for values of the control signal  $V_C(s)$  which results in saturation. The gain adjusted experimentally for this controller was  $k_{aw} = 16$ .

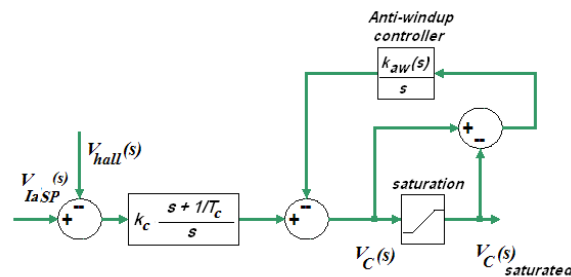


Figure 16. Block diagram of the anti-windup controller

The results obtained are shown at Fig. 17(a) that presents the measurement of electrical current and voltage in tachogenerator on practical tests performed with data acquisition using a step with amplitude of 8 V. The results obtained by simulation are presented at Fig. 17(b). It can be observed, the rapid response of the motor speed when the load is randomly introduced, abruptly, during the running of the motor after 20 seconds, and the withdrawal of the load, also abruptly, after 35 seconds. It also notes that comparing simulation and practice that there is a great similarity in the

responses and the PI control is efficient because eliminates the steady state error control, limits the electrical current when the motor is starting and presents rapid response. However, the experience results shows response relatively slower and lower armature current at motor. The possible reason is the imprecise value considered to load.

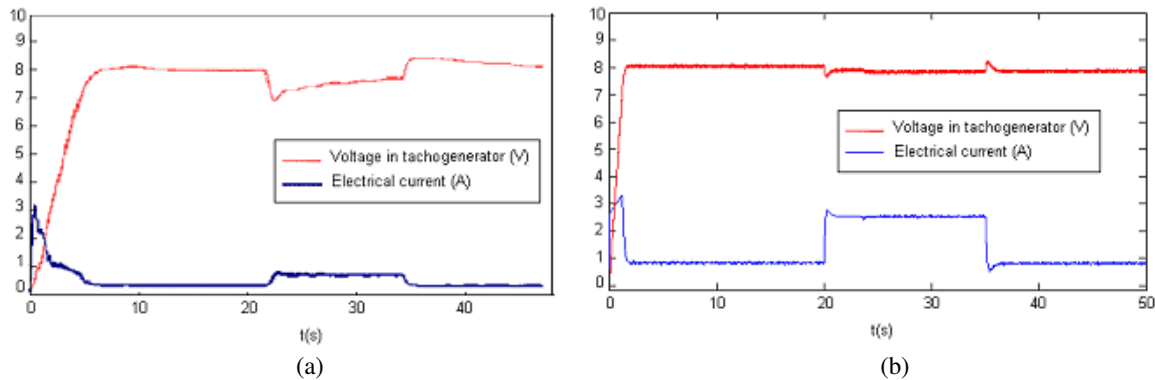


Figure 17. Results obtained using  $PI_s(s)$ ,  $PI_c(s)$ , anti-windup controller, filters and a step on input with amplitude 8 V  
(a) Practical results with data acquisition system (b) Simulation results

## 7. CONCLUSION

This work presented the development of experiments related to DC motor speed control system. The approach uses equipment similar to those typically employed in the industry showing a versatile solution, based on modern and efficient data acquisition system allowing the control by computer and presents relative accuracy and limitations in electrical current of DC motor, even when the system is subjected to variations in load.

The power electronic circuit used presents full-bridge with IGBT and integrated circuit IR2120, allowing the reversible drive of DC motor and regeneration, both controlled by PWM signal produced by programming.

The first experiment aims to make the students to understand a lot of functions available at the graphical interface software. At the first experiment, still before making control, has been developed a parameters estimation of system based on the method of weighted least squares. The estimation of parameters of the discrete state space representation was achieved by data acquisition of the voltage measured by tachogenerator and of the electrical current measured by Hall-Effect sensor. The validation of parameter estimation and mathematical modeling was done by comparing the results obtained in practice with those obtained by simulation using MATLAB™ software. Finally, at the last experiment, based on mathematical model, was performed the tuning of two PI controllers used for control the speed of DC motor and limit the electrical current from armature. The efficiency of the design and tuning of controllers were evaluated through the analysis of response to changes in reference speed (setpoint) and the variation of the load coupled to the motor shaft. Practical aspects were considered, such as the effect of saturation of the control signal and the presence of noise in the signals from the sensors. The work proposed solutions such as the introduction of anti-windup controller to minimize the effect of saturation and the introduction of filters to reduce the noise in the acquired data.

As a result of the application of laboratory's experiments in engineering courses there was clearly a higher learning of students and a growth interesting in researches related to control systems, power electronics and electrical machines.

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## 8. RESPONSIBILITY NOTICE

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