How to link the theory and practice of control engineering: Practices in real time and simulation.

I. I. Siller-Alcalá, R. Alcántara-Ramírez, J. Jaimes-Ponce, and J. P. Vaca-Pliego.

Abstract— The control theory is a hard subject for the students. It is difficult for them to relate the theoretical concepts with the control process in real time. The main target of this paper is to allow student links control theory with practice through a set of practice developed in Matlab in simulation and in real time for a heat transference module, which involve basics control concepts such as transfer function, perturbation, time constant, final value, steady state error, root locus, proportional and proportional integral control, frequency response analysis and identification by least square.

Keywords— Control System, Education, Experimental laboratory and Process Control.

I. Introduction

ALTHOUGH realistic simulation can provide valuable experience for the student learning control theory, but real experiments bring with them valuable lessons on the effects of noise, control constraints, nonlinear effects on control system performance. Visual feedback is also important. From a pedagogical point of view, real experiments that allow the design of the whole control law are more stimulating. In [1], a comparison between virtual labs (model simulation) and remote labs is presented. The authors examine a common experiment (ball and beam) from these two points of view and conclude that virtual labs are good to assimilate theory, but they cannot replace real process since a model is only an approximation which cannot reproduce all the aspects of the process, such as unexpected nonlinearities. To avoid these issues, laboratories that allow a student to interact directly with real processes should be used; this opportunity takes a fundamental role especially for engineering students.

Matlab and Simulink [8] are standard tools in the control community, and they are adopted in many basic and advanced courses, the Matlab environment is used in [2] to [7]. Since the controller is a Simulink model, the user does not spend time to learn a special programming language to implement the controller. Besides, through the use of Simulink graphical interface, a large set of blocks can be chosen and connected in a very easy way. In the Process Control Laboratory, the use of

Matlab has facilitated the implementation of classical and modern control [9], the friendly user interface, allows the user concentrates on the analysis and design of the control system.

The use of computer technology has become an extremely important tool in the teaching control theory. Engineering students need to be prepared for the increasing use of this technology in their future places of employment.

On the other hand, the heat transfer module to be controlled has the advantage of being simple to use, avoiding an excessive wiring and allow simulating the inputs and outputs of an industrial process. To control the energy applied to the module, a Pulse Wide Modulation PWM was used, due to the necessary heat control of the heating element, which switch is ON-OFF type and it is not possible to apply an analogue signal, like in the case sinusoidal signal of the electric energy supplied.

The authors consider that the present article provides interesting practices for those who are teaching the Control Systems.

II. Transfer Function of the Process

The process that it will be used in this paper, is a heat transfer module [10] shown in Fig. 1. The energy supplied to this module is constant and the way to vary is through a switch, controlling managing this switch the energy can be varied to change the temperature in the module. Then the way that energy is modulated is through a Pulse Wide Modulator (PWM).
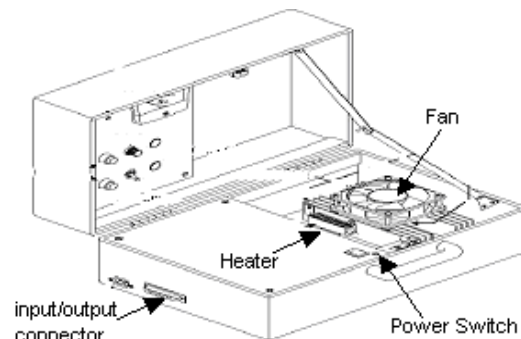

Fig. 1 Heat Transfer Module

A system like this is considered as a first order system given by the following Transfer Function [11].

$$G(s) = \frac{K}{Ts + 1} \quad (1)$$

In Fig. 2 shows the implementation of the open loop system in real time, in SIMULINK a MATLAB toolbox [8]. It is capable of providing different energy percentages.

The model for the open loop fundamentally consists of two parts: the one which sends the energy supplied to the heat transfer module and the one which receives the response of the open loop. This part receives the signals coming through the temperature sensor LM35 to filter, amplify it and convert it into temperature.

Once the conversion is done, the data are stores into a variable when the established time is over.

The section to establish the energy level consists on a constant block. This block orders to the Pulse Weight Modulator, how much energy will be supplied to the heat transfer module. This signal goes out trough the Output analogue block.

The fan is just used to cool the system when the trial is finished and does not function during the process. This signal and the ones coming from the PWM are sent to the exterior throughout the analogue output block and the configuration of this block is quite similar to the analogue input. Finally, with the scope block it is possible to observe the behaviour of the system.
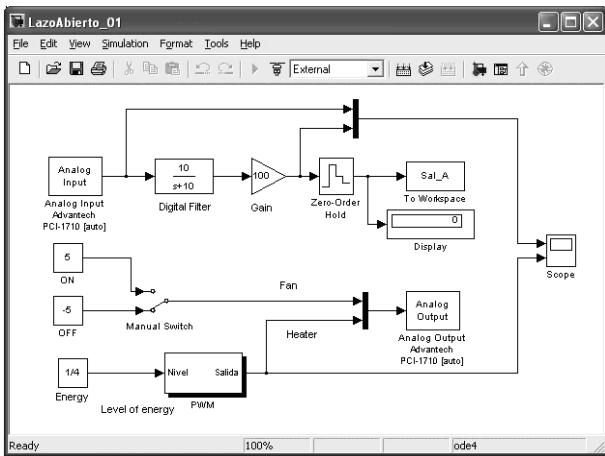

Fig. 2 Simulink model of open-loop control system for real time

Fig. 3 shows the module response when a 100% of the energy is delivered, from figure the student may obtain the time constant, on which the time of the answer of the system reaches the 63.2% of the final value [11], obtaining *T=750*. The final value minus the environment temperature, gives as a result the gain *K=56.176*, with both of this parameters the transfer function is obtained, the environment temperature acts as a disturbance, this is why in the open loop control system diagram in simulation. Fig. 4 the environment temperature is added to the output then, the output is given by

$$Y(s) = \frac{56.176}{760s + 1} U(s) + \frac{21.08}{s} \quad (2)$$
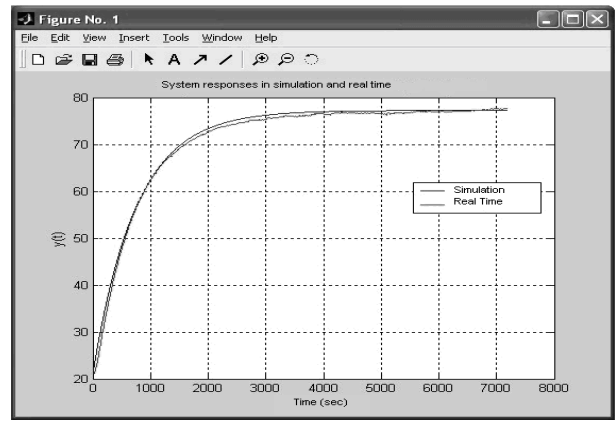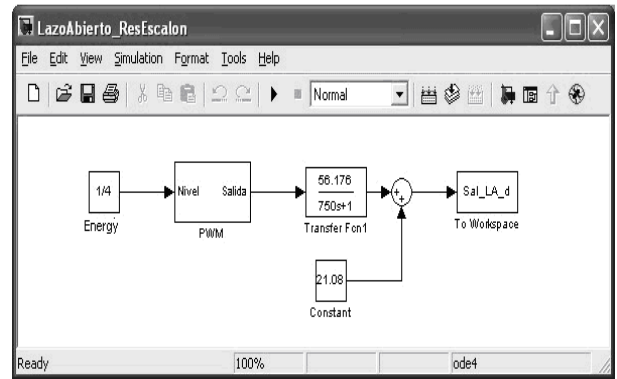

Fig. 3 System responses.

Fig. 4 Simulink model of open-loop control system for simulation

The response simulation and the response in real time are shown in Fig. 3, the congruence shown between the theory and the practice can be verified by the student.

When applied on a 100%, 75% and 50% of the energy, using the final value theorem [11], it is obtained *y(∞)=77.18, y(∞)=63.212, y(∞)=49.168.*

The response simulation in open loop with the energy percentages given above, are shown in Fig. 5, which are congruent with the theory.
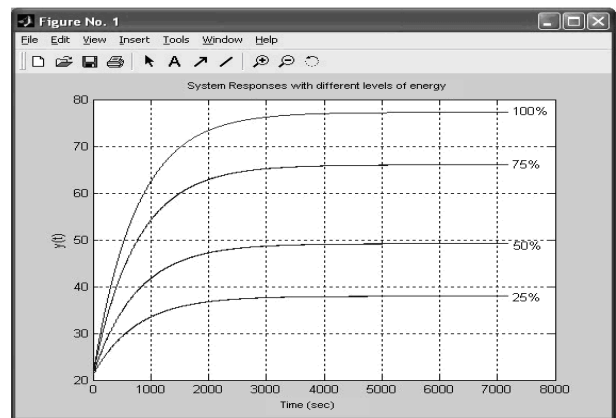

Fig. 5 Simulation system responses

The non linearity is present in all systems, in Fig. 6 it can be observed the system responses are not proportional, due to the system not being linear but still being possible to approximate it to a linear system.

III. PROPORTIONAL CONTROLLER

Fig. 7 shows the closed loop feedback control system with a proportional control, which was built in Simulink to get the simulation, where K_p varies taking values of *0.01, 0.02, 0.0267, 0.05, 1 y 2*. The step block is the reference to which it is desired the systems arrives, in other words, it is configured to get a final value of *50°C*. Fig. 8 shows the systems responses obtained with different K_p values.
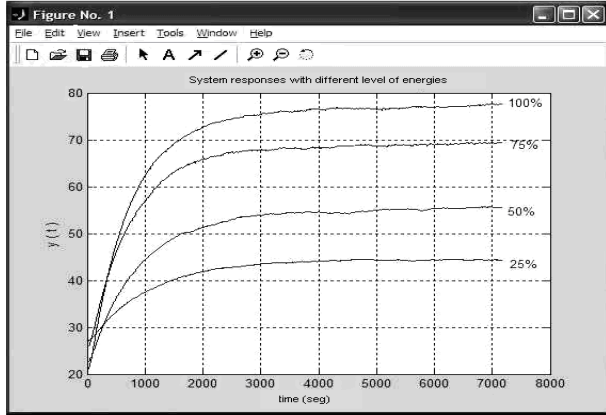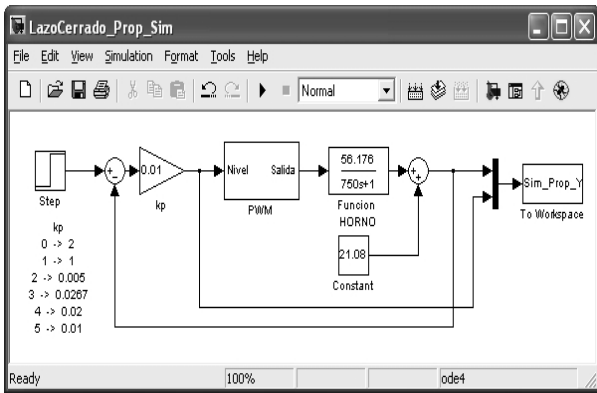

Fig. 6 System responses in real time

Fig.7 Simulink Model of simulation closed-loop feedback control system.

The student might be able to assimilate the theory in a better way, with the observation of the simulations and the following analysis. The output is given by

$$Y(s) = \frac{56.176 Kp}{750s+1}(R(s)-Y(s)) + \frac{21.08}{s} \qquad (3)$$

$$Y(s) = \frac{56.176 Kp R(s)s + 21.08(750s+1)}{s(750s + 56.176 Kp + 1)} \qquad (4)$$

Being *R(s)=50/s* and applying the final value theorem [11]. Then, when K_p =*1, 0.0267* and *0.05*, it is obtained *y(∞)=49.4941, y(∞)=38.43* and *y(∞)=42.4* respectively, as it is shown in Fig. 8. It is possible to observe that to reach *50°C* a large gain K_p is necessary. In Fig. 9 it can be observed that for bigger gains, more than a 100% of energy is being required, which on the practice it is not possible, when the controller asks for more than a 100% the PMW will only send a 100%. The implementation in real time by using SIMULINK is shown in Fig. 10.

Fig. 11 shows the system responses in real time with

different K_p values, it can be seen that the final values do not match with ones obtained in the theory, due to the non linearity, that the system presents.
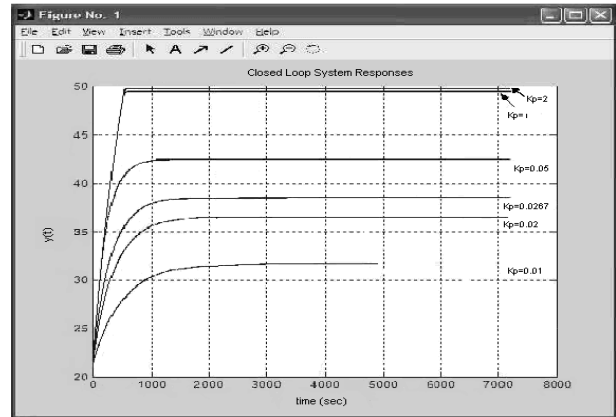

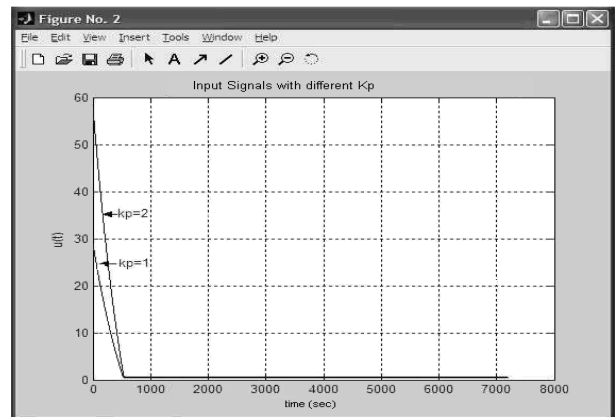Fig. 8 System responses varying the K_p values in simulation
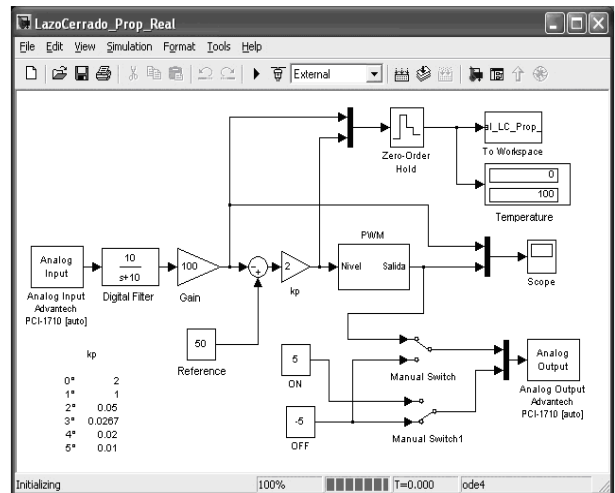

Fig. 9 Control signals in simulation

Fig. 10 Simulink Model in real time of the closed-loop feedback control system with PI Control.

Also, observe that when K_p=*1*, oscillations are present, as shown above, the controller requires an energy bigger than a 100% and will only be delivered at a 100%. In Fig. 12 the energy required is bigger than a 100% and negative, but the PMW will only send the 100% and 0% of energy, turning into an ON-OFF, then it can conclude that in practice, the gain can not be raised in order to eliminate the error.
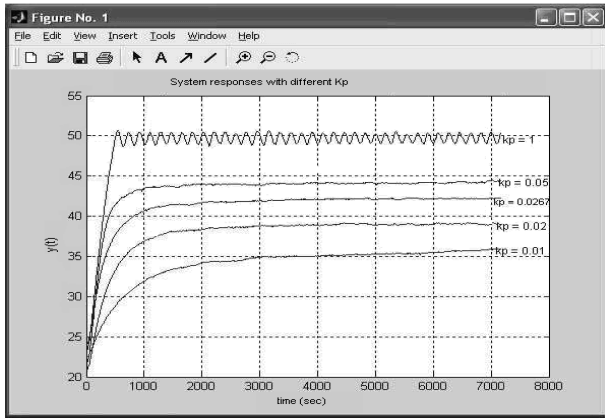
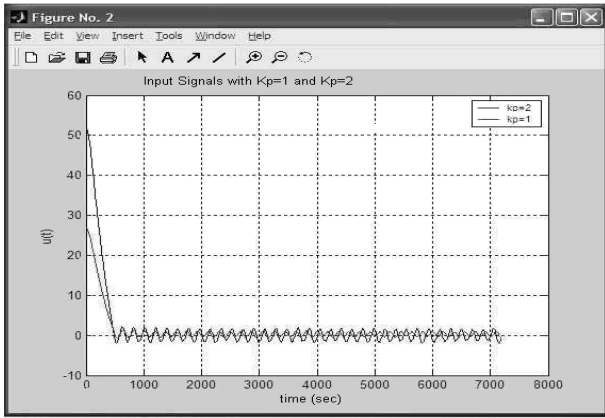Fig. 11 Responses in real time of the closed-loop feedback control system with PI Control varying K_p.

Fig. 12 Control signals in real time with $K_p=2$ and $K_p=1$

IV. PROPORTIONAL INTEGRAL CONTROLLER

The closed loop system diagram with a PI controller in simulation is shown in Fig. 13, a PID block where calculated proportional and integral gains will be accessed. It has been seen that output is given by

$$Y(s) = \frac{56.176Kp}{760s+1}(1+\frac{1}{Tis})(R(s)-Y(s))+\frac{21.08}{s} \quad (5)$$

Obtaining the output

$$Y(s) = \frac{56.176Kp(Tis+1)R(s)+21.08Ti(760s+1)}{Tis(760s+1)+56.176Kp(Tis+1)} \quad (6)$$

being $R(s) = 50/s$ because the desired temperature is 50°C. The final value or steady state can be determined

$$y(\infty) \rightarrow 50 \quad (7)$$

This means, for each value of K_p and T_i the system will tend to *50°C*, as well as the steady state will likely be zero thanks to the integral part. It is desired to obtain a response with the following specifications: peak overshoot $M_p =0.02$ settling time $t_s=3000$ because damping ratio $\xi=0.456$ and natural frequency $w_n=0.0022$, with these specifications $K_p=0.0267$ and $T_i =0.0267$ are obtained. The simulation of the system response is shown in Fig. 14, the specifications are reached. In Fig. 15 the implementation of the closed loop system with PI controller in real time is shown, Figs. 16 and 17 shown the

response and the control signal respectively and it can be observe that PWM is smaller than 100% and the dynamic behaviour of the real control is very similar to simulation.
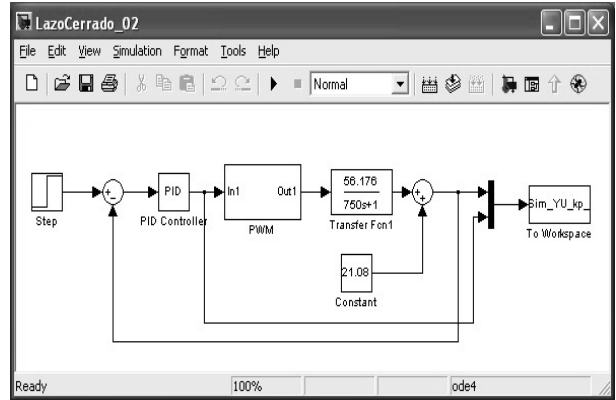

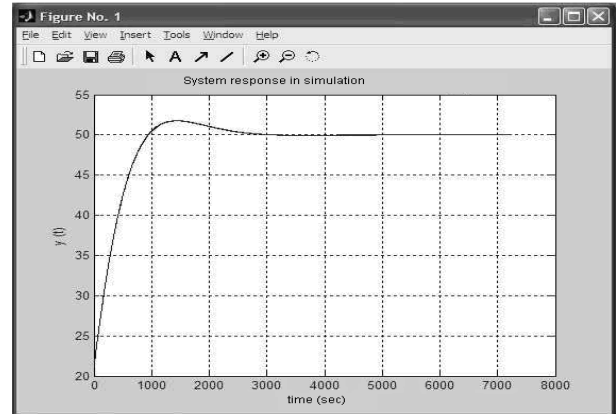Fig. 13 Simulink model in simulation of Control System with PI

Fig. 14 System response with PI controller in simulation

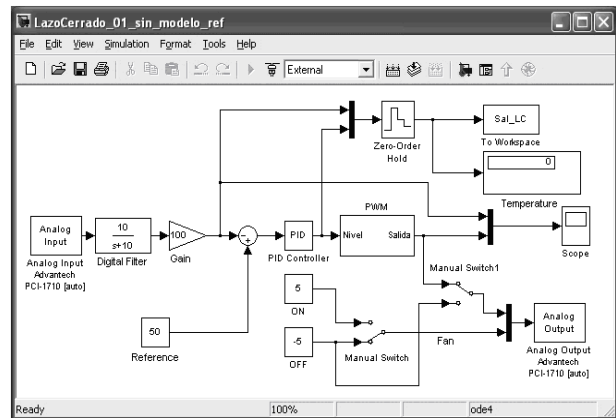Fig. 15 Simulink Model of the closed-loop control system with PI Controller in real time.

V. ROOT LOCUS OF THE OF THE CONTROL SYSTEM PI

The transfer function of the open loop system with a PI controller for the Heat Transfer Module is given by

$$\frac{Y(s)}{R(s)} = \frac{56.176Kp}{760s+1}(1+\frac{1}{Tis}) \quad (8)$$

Its transfer function of the closed loop system is given by the following equation

$$\frac{Y(s)}{R(s)} = \frac{56.176Kp(Tis+1)}{Tis(750s+1)+56.176Kp(Tis+1)} \quad (9)$$

This is a second order system, when K_p is varied, the poles of the closed loop system transfer function change, and it is obtained an overdamped, subdamped and critically damped system. Trough the root locus Fig. 18 is possible to see this and that the system always will be stable. An analysis of the transitory response can be carried out using a second order system of the form

$$\frac{Y(s)}{R(s)} = \frac{w_n^2}{s^2 + 2\xi w_n s + w_n^2} \quad (10)$$

In the above section the parameters of PI controller were chosen as $K_p = .0267$ and $T_i = 415.87$, the system has a zero in *-0.0024* and poles in *-0.0016±0.0014j* the system is subdamped.

Fig. 16 System response with PI controller in simulation

Fig. 17 Control Signal with PI controller in simulation

VI. FREQUENCY RESPONSE

The frequency response of the system is the response to sinusoidal inputs at varying frequencies. The output of a linear system is a sinusoid with the same frequency but with a different magnitude and phase. The frequency response is defined as the magnitude and phase differences between the input and output sinusoids. The sinusoidal input considered here, is given by

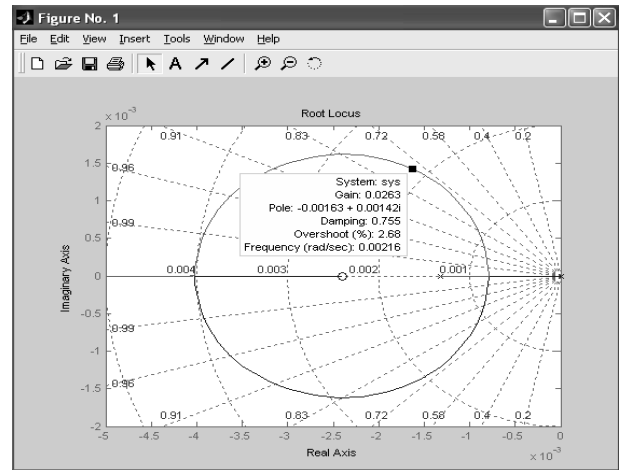$$U(s) = \frac{0.5}{s} + \frac{0.5w}{s^2 + w^2} \quad (11)$$

Fig. 18 Roots Locus.

In the Fig. 19 the implementation in real time of the system with this input is shown. The sinusoidal input (block Sine Wave) has amplitude 0.5, frequency *w*, which is variable and the offset 0.5. It has been chosen this input; due to the input system (energy) has not negative values (the system can not cool) neither bigger than 1 (more than 100% of energy), the inputs and outputs will be shown for different frequencies.
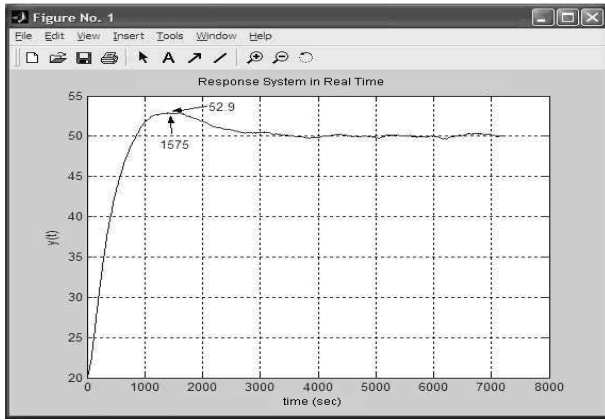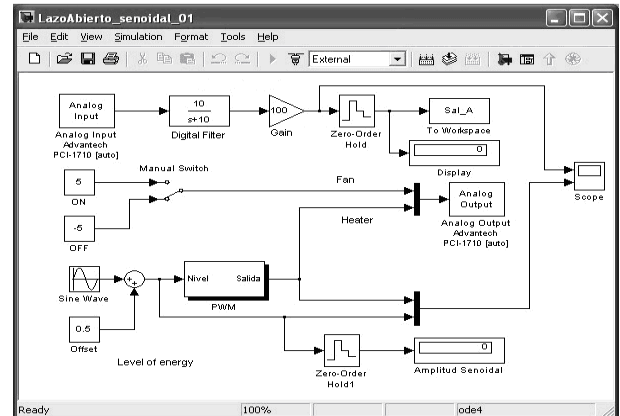

Fig. 19 Simulink model of open-loop control system in real time with sinusoidal input

The sinusoidal response magnitude will be the same as the sinusoidal magnitude input 0.5 from the gains obtained by the Bode diagram Fig. 22.

The sinusoidal inputs and the responses of the heat transfer module, are shown in Figs. 20 and 21, we have also draw the Bode diagram of the system Fig. 22, as well as the table shown in Table 1, once again proving the congruence between theory and practice. Also is intended with this practice that the student might realize, that not only the electric circuits amplify or reduce the signal.

VII. IDENTIFICATION BY USING LEAST SQUARE

We can also obtain the transfer function in z of the heat transfer module. The difference equation which describes the system is the following:

$$y(k) = au(k-1) - by(k-1) \quad (12)$$

To obtain the parameters, least square were used [12] and

[13] from the data obtained, we have that:

$$X_n = \begin{bmatrix} y(0) & u(0) \\ y(1) & u(1) \\ \vdots & \vdots \\ y(n-1)u(n-1) \end{bmatrix}, y = \begin{bmatrix} y(1) \\ y(2) \\ \vdots \\ y(n) \end{bmatrix}, \theta = \begin{bmatrix} -b \\ a \end{bmatrix} \quad (13)$$
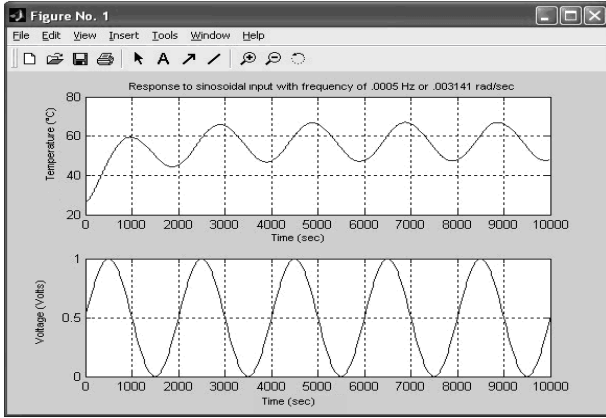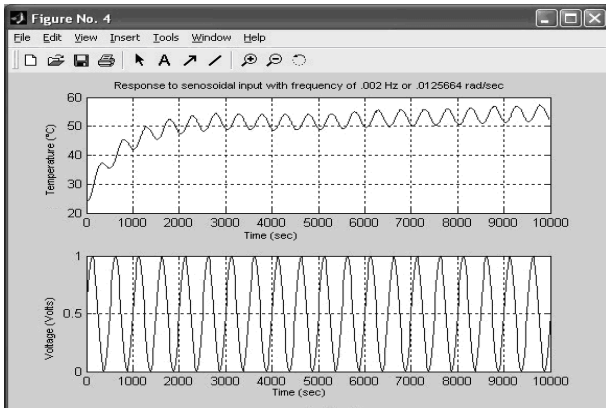

Fig. 20 Frequency of 0.003146 rad/sec

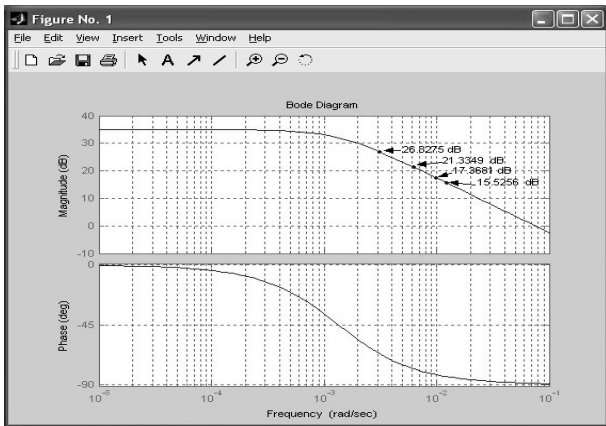Fig. 21 Frequency of 0.0125664 rad/sec

Fig. 22 Bode diagram.

TABLE I
RELATIONSHIPS BETWEEN BODE DIAGRAM AND RESPONSES.

Frequency	Magnitud of Response	Magnitud of Bode Diagram
.0031416 rad/seg	10.9753	26.8275 dB
.0062832 rad/seg	5.8306	21.3349 dB
.01005312 rad/seg	3.6929	17.3681 dB
.0125664 rad/seg	2.9871	15.5256 dB

To obtain the parameters vector θ, a program in Matlab was used which develops the following operations.

$$\theta = (X_n^T X_n)^{-1} X_n^T y \quad (14)$$

Obtaining

$$\frac{Y(z)}{U(z)} = \frac{1.0246z^{-1}}{1 - .9835z^{-1}} \quad (15)$$

The Fig. 23 shows the heat transfer module response, when a 100% of the energy is sent as well as the output of the identified Eq.12.
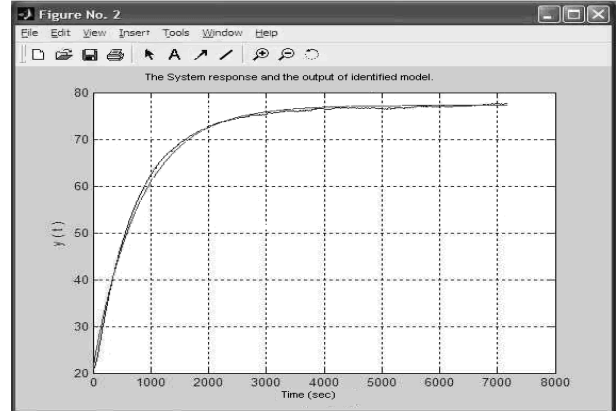

Fig. 23 The heat transfer module response and the output of identified model.

VIII. CONCLUSION

This article is presented in a nice way, throughout practices, which use some of the Basic concepts of the Control theory and pretend to link the theory with the practice. In order to achieve this objective, a heat transfer module and the Matlab Simulink was used.

We can conclude that the simulation is quite important to assimilate the theoretical concepts (Transfer function, disturbance, time constant, final value, root locus, steady state error, proportional control as well as integral proportional control) visually, throughout Simulink, but it is known that a real time process enriches the teachings and will become more attractive for the student. The Simulink is quite simple to use, due to the advantage of not having to learn a new language, thanks to this, the student will only have to concentrate on the design and the analysis. The PMW modulation was developed using the blocks from the Matlab package, being possible to have better visualization of the control concepts. In the case of real time, there is no need of concern for either the hardware or complicated connections.

We can observe that the real time control is important, due to the presence of factors as signal control restrains, nonlinear effects and noise which were not previously contemplated on the simulation. The simulation has a great importance, because it becomes an aid during the teaching-learning process to reinforce the theoretical concepts and to design a controller with the specifications given, which can be applied to the real system, showing some of the differences in the responses, since mathematical model generally catches the main features of the system, the students can evaluate the

differences between the model and the real process and tune some parameters to obtain a controller which works better with the real process. During the practices, students seem to be very excited, basically because they can put in practice their control theory knowledge through real process. The authors consider that the present article provides interesting practices for those who are teaching the Control Systems.

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