Learning Switching Control: A Tank Level-Control Exercise

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***Abstract*—A key topic in multicontroller strategies is the mechanism for switching between controllers, depending on the current operating point. The objective of the switching mechanism is to keep the control action coherent. To help students understand the switching strategy involved in multicontroller schema and the relationship between the system dynamics and the switching structure, this paper proposes a student practical where basic linear control knowledge and a simple switching strategy are applied to an educational nonlinear control problem, that of controlling the level in a tank. Evaluation provided by the students is also included.**

***Index Terms*—Control engineering education, level control, nonlinear systems, PID control, switching systems.**

I. Introduction

NONLINEAR system dynamics can be approximated by a set of linear models, which represent the system dynamics around a certain operating point [1]. Multicontroller strategies allow nonlinear systems to be controlled by applying basic linear control strategies instead of having to design complex nonlinear controllers. Furthermore, with little additional knowledge, a switching multicontroller strategy can be implemented, in which a set of linear controllers is included in a structure with: 1) a supervisory layer that decides the active controller at any moment, and 2) a switching mechanism to maintain coherent (and usually continuous) control action when a switch is made.

Switching control is a versatile strategy that has been applied successfully to a wide variety of engineering areas, among them the biochemical [2] and solar collector fields [3] and marine navigation [4]. To help students in the sometimes difficult task of understanding the theoretical concepts of automatic control, control engineering courses include simulations and experiments performed on scale model processes or even on real industrial systems [5], [6]. The main objective of this paper is to propose an educational exercise to support the learning of the theoretical concepts of switching control. This exercise allows students to understand, through simulations and experiments, the importance of each element in a switching control structure and how these are interrelated. It was applied in the academic year 2009–2010 at the University of Almería, Almería, Spain, in two different Master's courses—one in chemical engineering and one in industrial computing engineering.

Previous offerings of these courses featured an optional exercise that asked students to apply switching control strategy to a level-control problem using a scale model plant. Unfortunately, several students chose not to do the exercise, and those who did encountered considerable problems in solving it correctly. The exercise was then modified so as to lay out the steps to be followed, and so that students discover the important concepts by performing the activities summarized in this paper.

A well-designed experiment allows students to discover switching-related concepts intuitively. They learn the following.

1) Multicontroller switching strategies are an acceptable approach to control nonlinear systems.
2) Controller design is directly influenced by the partition of the nonlinear system dynamics into operating regions.
3) The rules for switching between controllers are related to the system evolution between these operating regions.
4) The switching signal is related to the system dynamics evolution.
5) Switching control can improve the overall performance.
6) A mechanism is necessary to guarantee the control signal continuity.
7) Some switching requirements must be taken into account to avoid fast switching.
8) Switching strategies can be applied not only to feedback action, but also to feedforward action.

The proposed exercise, performed on a scale model plant, also allows students to apply their theoretical linear control knowledge and to confirm that: 1) linear controller performance can only be guaranteed inside the operating region for which it was designed; 2) an individual linear controller presents considerable limitations for dealing with nonlinear systems across their whole operating range; 3) control strategies applied in simulations can be applied to real plants; and 4) for operation in a real plant, physical limitations must be taken into account.

The exercise consists of a classical practical experiment using a tank level control subjected to disturbances. When performed step-by-step as defined below, key-switching control concepts appear in an intuitive way.

II. Switching Control

A switching control scheme is usually composed of one or more banks of local controllers, a supervisory layer that defines which controller in each local bank should be included in the control loop, and finally a switching mechanism that guarantees

Manuscript received January 14, 2011; revised May 13, 2011; accepted June 20, 2011. Date of publication August 01, 2011; date of current version May 01, 2012. This work was supported by the Spanish Ministry of Science and Innovation under National Plan Projects DPI2010-21589-C05-04.

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Digital Object Identifier 10.1109/TE.2011.2162239

the control signal continuity when switches are made. The role of each element is analyzed in [7].

Useful textbooks treating the theoretical contents of switching control systems are [8] and [9]. Reference [10] is a recommended introductory lecture in switching control theory that was used in the courses described in this paper. The exercise proposed here uses the switching mechanism defined in [3], although the literature offers several switching mechanisms that could be also applied with similar results [7].

In the student practical, two PI controllers for the operating points i and j, respectively, are considered, where the state-space discrete-time representation for both controllers is given as follows:

$$x_i(t+1)=A_ix_i(t)+B_ie(t) \quad u_i(t)=C_ix_i(t)+D_ie(t) \qquad (1)$$
$$x_j(t+1)=A_jx_j(t)+B_je(t) \quad u_j(t)=C_jx_j(t)+D_je(t) \qquad (2)$$

with x_i and x_j representing the controllers states; $e(t)$ being the tracking error signal at time t (the controller input signal); u_i and u_j being the controllers' outputs; and A_i, A_j, B_i, B_j, C_i, C_j, D_i, and D_j being matrices of suitable size that define the controller dynamics. Suppose that controller i is active at the corresponding operating point. Then, the supervisory layer decides to switch to controller j at instant t_0. Therefore, it is desirable that $u_j(t)=u_i(t)$ to achieve bumpless transfer.

Using (1) and (2), it can be seen that to obtain that equality, the state of controller j at time instant t_0 should be recalculated as follows:

$$x_j(t_0)=C_j^{-1}\left(u_i(t_0)-D_je(t_0)\right). \qquad (3)$$

Obviously, in order to obtain (3), matrix C_j must be square. In a simple PI controller, this condition is fulfilled since the controller has one output and one state, but when the number of system outputs is different from the number of system states, matrix C_j is not invertible and (3) cannot be applied. To extrapolate (3), the following expression is used [3]:

$$\begin{aligned} x_j(t_0-n+1) &= O^{-1}\left\{\begin{pmatrix} u_{j(t_0-n+1)} \\ u_{j(t_0-n+2)} \\ u_{j(t_0-n+3)} \\ \cdots \\ u_{j(t_0)} \end{pmatrix} - \begin{pmatrix} D_j \\ C_jB_j \\ C_jA_jB_j \\ \cdots \\ C_jA_j^{n-2}B_j \end{pmatrix} e(t_0-n+1) \right. \\ &\quad - \begin{pmatrix} 0 \\ D_j \\ C_jB_j \\ \cdots \\ C_jA_j^{n-3}B_j \end{pmatrix} \\ &\quad \times e(t_0-n+2-\ldots-000\ldots Dje(t0) \end{aligned} \qquad (4)$$

where continuity is imposed in the control signal keeping $u_j(t_0=u_i(t_0)$, whereas the rest of the values of signal $u_j(t)$ until $t=t_0-n+1$ are calculated as if controller j had previously been the active controller. Finally, O is the observability matrix, which must be full-rank. More details of this procedure can be found in [3].

It is important to highlight that the use of a switching mechanism involves certain limitations, and when applied to more complicated systems, special attention should be paid to stability issues.

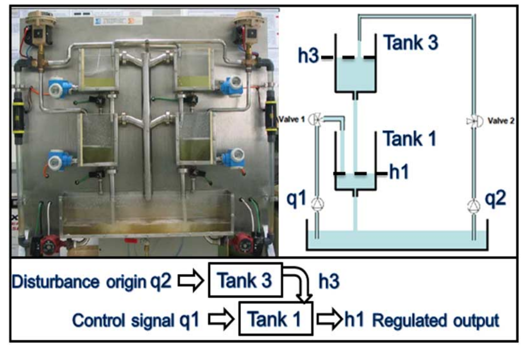

Fig. 1. Quadruple-tank scale model and experimental configuration.

III. Plant Description

The quadruple-tank scale model consists of four interconnected water tanks, as shown to the left of Fig. 1; it has been variously applied to control education [11], [12]. The exercise proposed here is to control h_1 by means of manipulating the pump q_1 flow, under disturbances produced by manipulation of pump q_2. The plant configuration is shown on the right-hand side of Fig. 1.

A quadruple-tank scale model is available to the students as a part of the AutomatL@bs project, a network of virtual and remote laboratories for teaching and learning of control engineering through which several universities share their educational resources.[1]

For students to test through simulation the control strategies they have developed, they need the nonlinear system model. In [13], the quadruple-tank process is modeled through differential equations that represent its mass balances

$$\frac{dh_1(t)}{dt}=-\frac{a_1}{A_1}\sqrt{2gh_1(t)}+\frac{a_3}{A_1}\sqrt{2gh_3(t)}+\frac{1}{A_1}q_1(t) \qquad (5)$$
$$\frac{dh_3(t)}{dt}=-\frac{a_3}{A_3}\sqrt{2gh_3(t)}+\frac{1}{A_3}q_2(t) \qquad (6)$$

where $h_1(t)$ and $h_3(t)$ are tanks 1 and 3 levels [cm], a_1 and a_3 are tanks 1 and 3 output sections [cm^2], A_1 and A_3 are tanks 1 and 3 sections [cm^2], g is the gravity acceleration constant [cm/s^2] and $q_1(t)$ and $q_2(t)$ are pumps 1 and 2 flows, respectively [cm^3/s]. In this example, $A_1=A_3=840.16$ [cm^2], $a_1=2.1382$ [cm^2] and $a_3=0.9503$ [cm^2]. Linearizing (5) and (6) around a certain operating point $(h_1^0,q_1^0),(h_3^0,q_2^0)$, the following transfer functions are obtained:

$$G_{a1}(s)=\frac{\overline{H_1}(s)}{\overline{Q_1}(s)}=\frac{c_1}{T_1s+1} \qquad (7)$$
$$G_{a2}(s)=\frac{\overline{H_1}(s)}{\overline{Q_2}(s)}=\frac{c_1}{(T_3s+1)(T_1s+1)} \qquad (8)$$

where $G_{a1}(s)$ relates the level variation of $h_1,\overline{H}_1$ with the volumetric flow variation of $\mathrm{q}_1,\overline{Q}_1$, while $G_{a2}(s)$ relates $\overline{H}_1$ with the volumetric flow variation of $\mathrm{q}_2,\overline{Q}_2$. Finally, $T_i=(A_i/a_i)\sqrt{2h_i^0/g}$ defines the system time constant value, whereas $c_i=T_i/A_i$ defines the system static gain constant value, and h_i^0 tank i the level around which the equation has been linearized $(i\in\{1,3\})$.

[1]http://lab.dia.uned.es/automatlab/

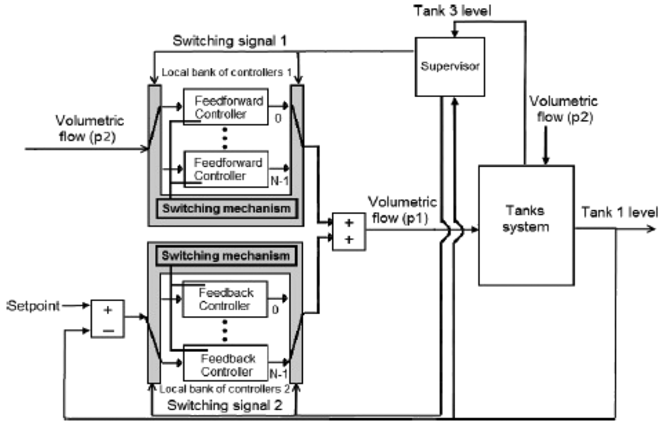

Fig. 2. Switching control scheme implemented.

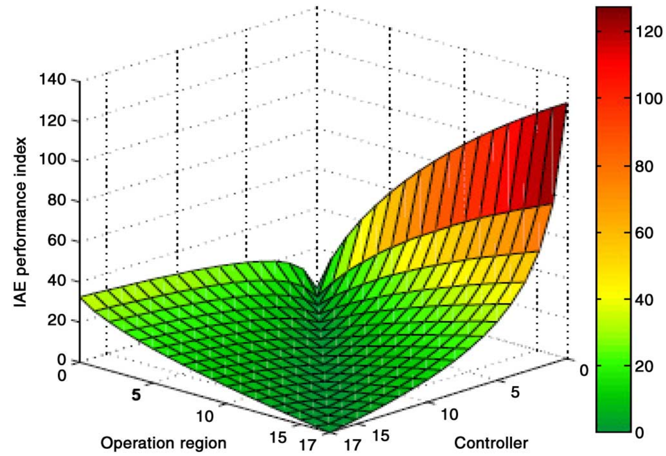

Fig. 3. Analysis of the deviation of each controller from the theoretical desired response across the whole operating range.

TABLE I
$q_1 - h_1$ MODELS AND LOCAL BANK OF FEEDBACK PI CONTROLLERS

i	h_1 (cm)	Linear model	PI controller
0	[0, 1]	$\frac{0.021}{18s+1}$	$\frac{21.32\,(18s+1)}{18s}$
1	(1, 2]	$\frac{0.029}{26s+1}$	$\frac{21.73\,(26s+1)}{26s}$
...	...	...	...
16	(16, 17]	$\frac{0.087}{74s+1}$	$\frac{21.24\,(74s+1)}{74s}$
17	(17, 18]	$\frac{0.089}{76s+1}$	$\frac{21.20\,(76s+1)}{76s}$

As can be observed in (7) and (8), their dynamics depend on h_1^0 and the pair (h_1^0, h_3^0), respectively. Linear approximations to the system dynamics for a certain operating point can also be obtained empirically through several step-response experiments.

IV. Proposed Experimental Steps

The switching control structure for the exercise is shown in Fig. 2. Two independent local banks of controllers are defined: one for feedback control action and the other one for feedforward control action. Two banks are necessary because feedback and feedforward actions do not share a common operating space partition, as students will notice when performing the experiment.

A. *Feedback Control Strategy*

First, students have to apply (7) to obtain a set of linear models for different level values in tank 1, i.e., for different operating points. Here, a division into 18 operating regions related to each centimeter of level in the tank is proposed. The number of operating regions and the unitary distance between them was chosen for an educational reason: to set an explicit unitary relation that students can easily identify, among the level, the switching signal, the operation region and the active controller.

Table I shows the set of linear models obtained using (7) with a h_1^0 value equal to the higher-level value in its operating region interval. Furthermore, it shows the set of PI controllers designed for each of these by the pole-zero cancellation method to obtain a system closed-loop time constant of 40 s for all the operating regions. These PI controllers, defined as transfer functions, will be converted into state-space form and implemented in discrete time using typical numerical approximations of the integral operator with a sample time equal to 2 s to perform the simulations. Notice that, for simulations, the nonlinear models described by (5) and (6) are used.

Prior to performing the comparative simulation proposed in Section IV-B, students should analyze the suitability of each of these controllers across the whole operating range. All the controllers were designed to have a closed-loop time constant equal to 40 s. Therefore, students are asked to perform an analytical comparison in terms of the deviation from the desired system closed-loop response. Controllers were applied at each individual operating region, and the plant output response to a 1-cm step was compared by means of the *Integral of Absolute Error* (*IAE*) performance index to the theoretical desired response. As can be observed in Fig. 3, the best *IAE* indices are found on the diagonal, where each controller matches the operating region for which it was designed.

The various steps proposed to understand the switching design procedure are described as follows.

Fixed Controllers: Students should, at the least, perform simulations with an aggressive, a conservative, and an average controller across the whole operating range in order to understand nonlinear behavior. In Fig. 4, simulations performed with controllers designed for operating regions 0, 8, and 17 are shown. These simulations were performed in MATLAB, a high-level technical computing environment developed by The MathWorks, Inc.

The aggressive controller (dashed line) overshoots at each setpoint step. The conservative controller (dotted line) does not overshoot, but its global performance can be improved. The average controller (dotted-dashed line) avoids overshoots and improves the conservative controller performance, but the response is slow in low flow operation regions, as can be observed in the first reference step.

Multicontroller Without a Switching Mechanism: Students define the operating regions of the feedback strategy according to the set of linear models obtained previously (considered as a division of the nonlinear dynamics into operating regions) and then design a controller for each region. A simple feedback switching rule can be defined attending to the value of

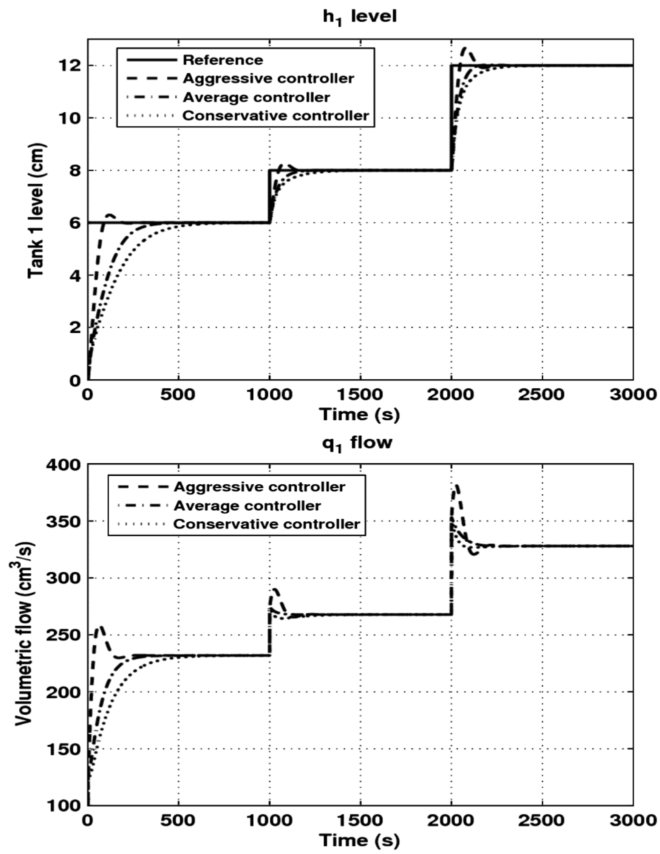

Fig. 4. Feedback simulation: fixed controllers.

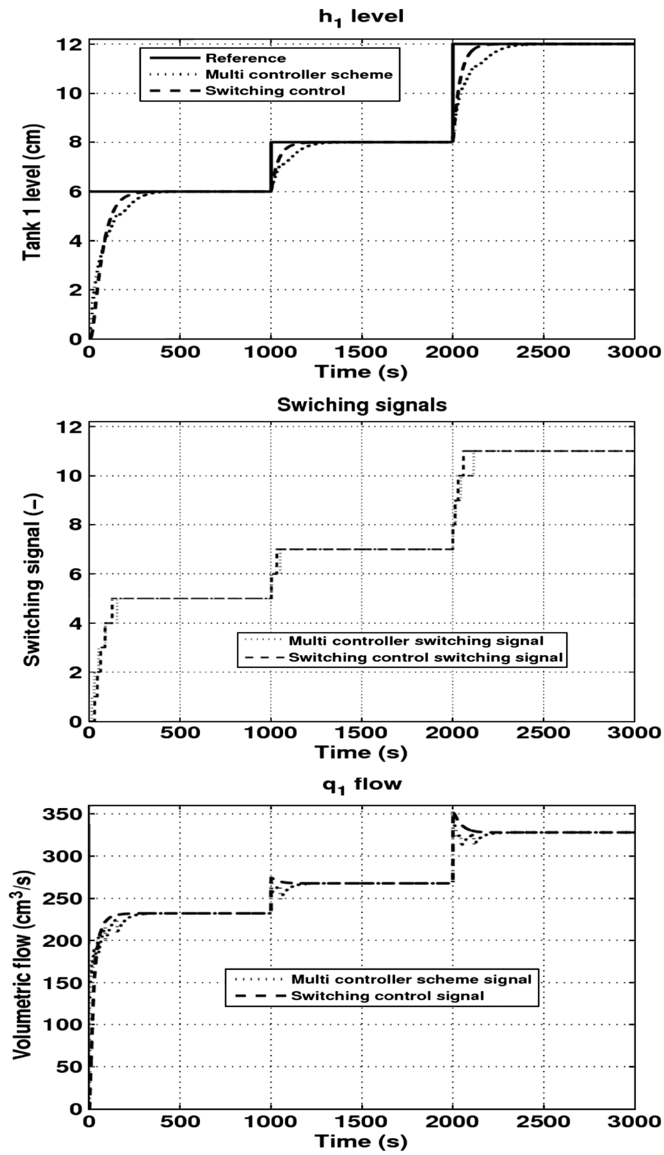

Fig. 5. Feedback simulation: multicontroller scheme without switching mechanism and switching control.

h_1, and a dead zone with a width of 0.1 cm is set around each boundary value to avoid fast switching. Defining a dead zone around switching boundaries means that in order to avoid undesirable fast-switching effects, the system must surpass not only the switching boundary that defines the operation point, but also an additional zone (in this case, 0.1 level cm). However, the dead zone is not applied when a switch is made to a different operating region.

Some interesting issues can be observed by the students when this multicontroller scheme without a switching mechanism is applied (dotted line in Fig. 5). One of these is that an undesirable transient is observed in the control signal due to the new active controller states not having been previously recalculated to guarantee continuity in the control signal. Also, it can be observed that these nondesired discontinuities in the control signal cause a poor behavior in the system response. Moreover, when operating a real plant, these discontinuities could result in a considerable deterioration of the actuator due to the fast flow variations (bottom image in Fig. 5).

Switching Control: The switching mechanism explained in Section II is applied to the multicontroller scheme (dashed line in Fig. 5). In this scheme, whenever a switch is made, the new active controller states are recalculated in order to keep the control signal coherent with its past evolution. Hence, students will realize that the control signal discontinuities resulting from a switch being made disappear thanks to the effect of the switching mechanism, thus improving the behavior across the whole operating range. Furthermore, the system closed-loop time constant is more homogeneous because all the controllers were designed to have a common closed-loop time constant in their own operating region and to only operate within that region.

B. Feedforward Control Strategy

Next, a set of classical parallel feedforward controllers are designed to reject the disturbances caused in tank 1 (h_1) by the flow from pump 2 (q_2). Each feedforward controller, supposing a perfect model, is defined as

$$\mathrm{FF}(s) = \frac{-G_{a2}(s)}{G_{a1}(s)} = \frac{\frac{c_1}{(T_3s+1)(T_1s+1)}}{\frac{c_1}{(T_1s+1)}} = \frac{-1}{T_3s+1} \tag{9}$$

where $G_{a2}(s)$ is the transfer function relating changes in q_2 to changes in h_1, (8), and $G_{a1}(s)$ is the model that relates changes in q_1 to changes in h_1, (7). After applying (9), a set of 18 feedforward controllers that depend on the value h_3 is obtained.

Table II shows the set of linear models obtained using (8) with h_1^0 and h_3^0 values equal to the higher-level value in its h_1 and h_3 operating region interval, respectively. These models relate the flow q_2 with the level h_1 according to the current h_1 and h_3

TABLE II
$q_2 - h_1$ MODELS

	i	0	...	17
		h_1(cm) [0, 1]		
j	$h_3\ (cm)$			
0	$[0,1]$	$\frac{0.021}{(40s+1)(18s+1)}$	...	$\frac{0.089}{(40s+1)(76s+1)}$
1	$(1,2]$	$\frac{0.021}{(57s+1)(18s+1)}$	...	$\frac{0.089}{(57s+1)(76s+1)}$
...	...	...	...	...
16	$(16,17]$	$\frac{0.021}{(165s+1)(18s+1)}$	...	$\frac{0.089}{(165s+1)(76s+1)}$
17	$(17,18]$	$\frac{0.021}{(170s+1)(18s+1)}$	...	$\frac{0.089}{(170s+1)(76s+1)}$

TABLE III
LOCAL BANK OF FEEDFORWARD CONTROLLERS

i	h_3 (cm)	FF controller	...	i	h_3 (cm)	FF controller
0	[0, 1]	$\frac{-1}{40s+1}$	...	16	(16, 17]	$\frac{-1}{165s+1}$
1	(17, 18]	$\frac{-1}{57s+1}$	...	17	(17, 18]	$\frac{-1}{170s+1}$

values. Table III presents the feedforward controller designed by applying (9) for each h_3^0-level value, with a 0.1-cm dead zone being set around its boundaries. As can be observed in (9), h_1 level has no influence in the feedforward controller, while the h_3 level defines the active feedforward. Due to lack of space, Tables II and III only show a brief description of the resulting disturbance models and feedforward controllers.

Students have to perform several simulations, for different tank-1 levels and flow steps in pump 2. Three comparative experiments with constant h_1 references were performed in Fig. 6. Variations of q_2 produce variations in h_3 level, causing errors in the feedback tracking of the h_1-level reference. For this reason, the increments of q_2 shown in the bottom image in Fig. 6 are compensated for with decrements of q_1 through the feedforward control action, as shown in the middle image of Fig. 6.

Fig. 6 presents an interesting graphical representation of the way in which the behavior of the fixed feedforward controllers (dashed, dotted-dashed, and dotted black lines) deteriorates, resulting in longer transients, as they get farther from the operating region for which they were designed. The multicontroller scheme without the switching mechanism and the switching feedforward controllers (solid and dotted gray lines) can adapt their response to the current operating region. They present a common response during the first step due to the fact that h_3 remains inside operating region 0. However, in the next steps, switches are made between operating regions, causing undesired transients in the control signal. These cannot be rejected by the multicontroller scheme, and so the plant output response deteriorates. However, the switching control recalculates the new controller states at each switch between operating regions, rejecting the control signal discontinuities and providing acceptable performance across the whole operating range.

V. SCALE MODEL EXPERIMENT

The scale model system presents mechanical limitations and nonlinearities related to the pumps. For this and other reasons,

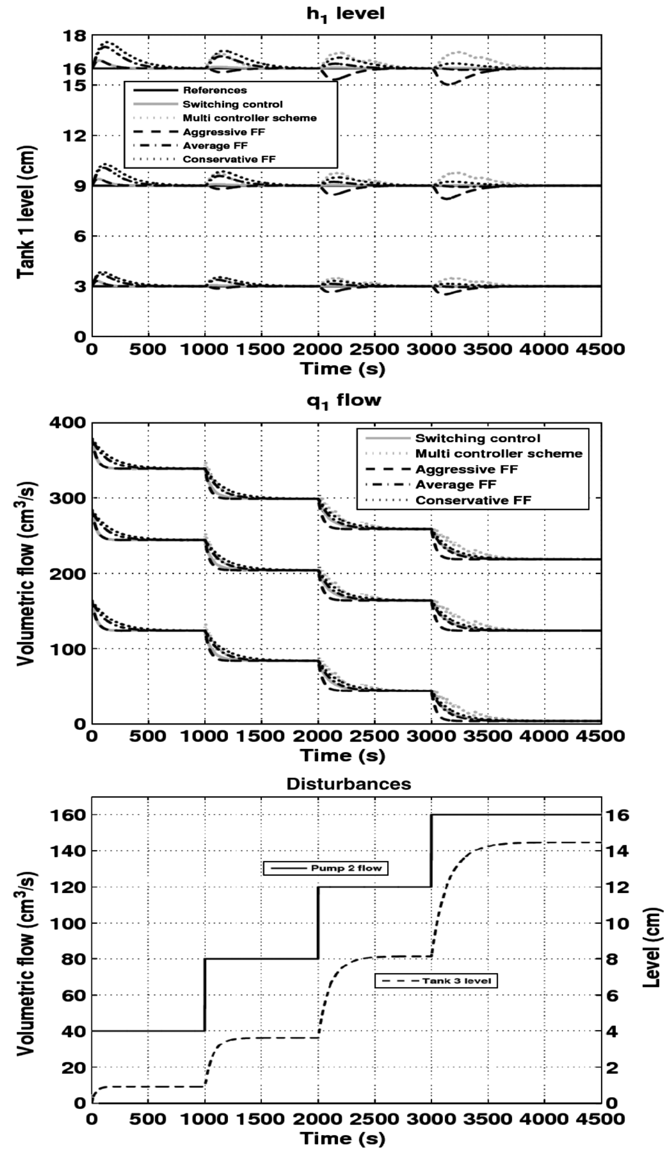

Fig. 6. Comparison of the feedforward control strategies.

the model at each operating point differs slightly from those in (5) and (6). Therefore, the linear approximations obtained for each operating region by means of (7) and (8) should be corrected. To make this difference clear, students should perform an empirical scale-model identification experiment and compare theoretical and empirical results, as shown in Table IV. The disturbance models and controllers must be corrected in the same way as for the feedback strategy.

Since it is advisable to keep the flow over 220 cm^3/s, operating regions for levels below 4 cm were not included due to centrifugal pump mechanical limitations.

Fig. 7 shows a scale-model switching-control experiment in which several switches are made, moving between operating regions. Students will notice that the switching controller is not able to achieve the theoretical results due to the plant mechanical characteristics. However, the system response is acceptable across the whole operating range, and setpoint steps of considerable magnitude can be made.

The switching feedforward experiment performed on the scale model plant is shown in Fig. 8. Several q_2 flow steps are

TABLE IV
$q_1 - h_1$ THEORETICAL AND EMPIRICAL LINEAR MODELS

h_1 (cm)	Simulation	Scale model	…	h_1 (cm)	Simulation	Scale model
(4, 5]	$\frac{0.047}{40s+1}$	$\frac{0.069}{35s+1}$	…	(16, 17]	$\frac{0.087}{74s+1}$	$\frac{0.1095}{73s+1}$
(5, 6]	$\frac{0.051}{44s+1}$	$\frac{0.074}{38s+1}$	…	(17, 18]	$\frac{0.089}{76s+1}$	$\frac{0.1099}{74s+1}$

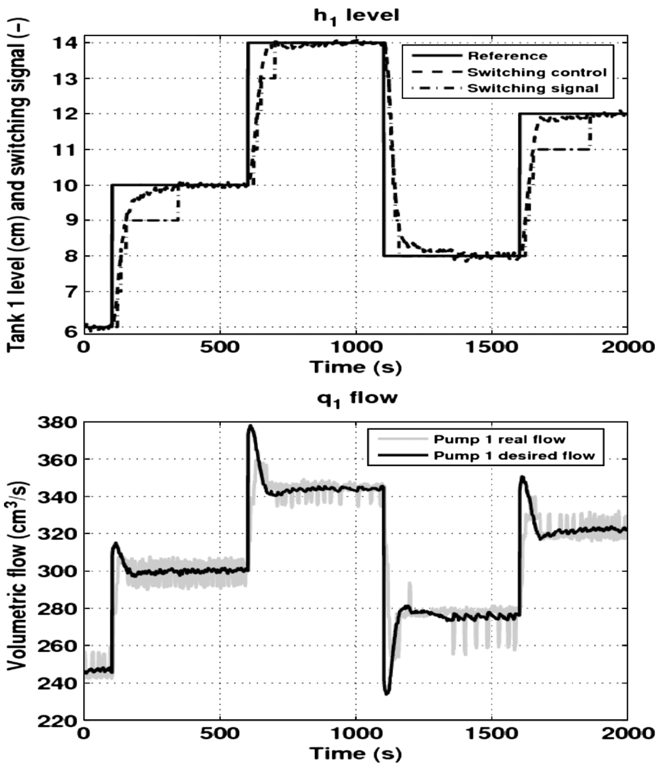

Fig. 7. Scale-model switching-control feedback experiment.

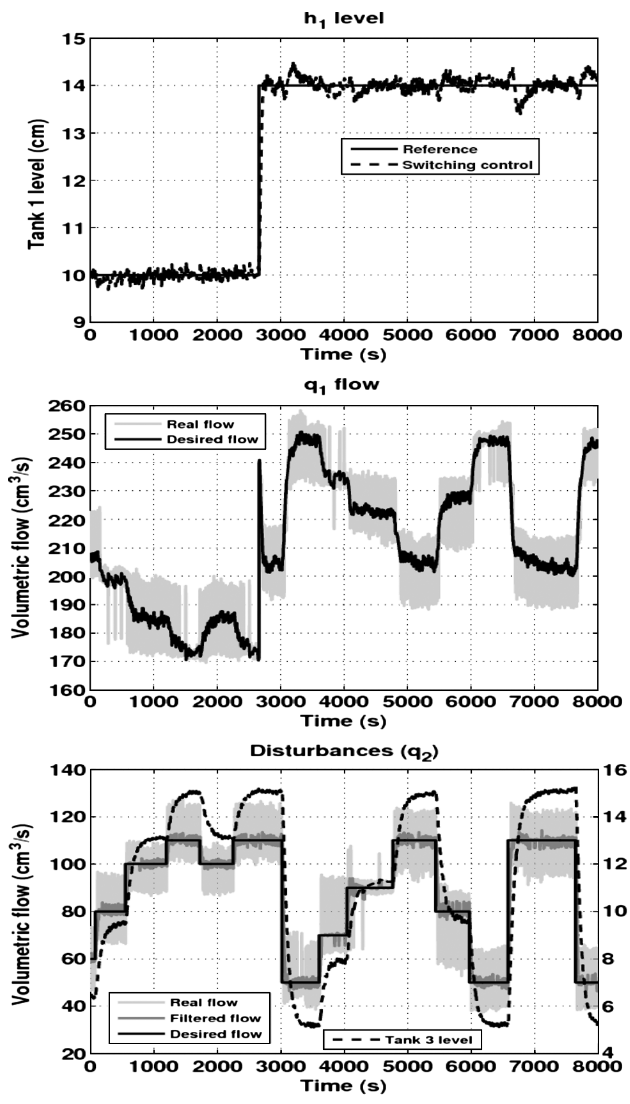

Fig. 8. Scale-model switching-control feedforward experiment.

performed manually (desired disturbance flow) at two different h_1 setpoint values (10 and 14 cm). Due to the oscillatory pump behavior, a low-pass filter with a cutoff frequency of 0.314 rad/s was applied, reducing the q_2 oscillations amplitude by around 80%.

VI. EVALUATION

Comparing the results of this 2009–2010 academic year to previous years, some interesting conclusions can be highlighted.

1) The percentage of students who did the optional exercise increased from 58% to 83%.
2) Of these, the number of students having trouble finishing the exercise decreased from 47% to 8%.

Furthermore, students from previous years used to focus on the fact that the switching mechanism allows transients in the control signal to be avoided and gives an acceptable control system behavior. However, students who did the proposed exercise obtained a deeper insight into the nature of switching control and a better knowledge of how to apply this strategy. Also, the issues raised by these students while performing the exercise show a deeper understanding of the problem addressed.

The inclusion of a detailed description of steps to take to solve the exercise simplifies the problem for the students. The gradual approach from a control system based on a fixed controller for the whole operation region to a switching controller strategy, including a switching mechanism, is the same that most students use to deal with a nonlinear problem. Implementing the different control strategies in the same exercise and comparing their results helps students to understand each component of a switching control strategy.

Two sets of 25 students completed a questionnaire whose results are shown in Table V. The students considered that with this new methodology, switching concepts are easy to learn.

TABLE V
STUDENT TASKS AND EDUCATIONAL OBJECTIVES

*	Question	A	B	C	D	E
1	Ease to learn concepts	3%	0%	4%	31%	62%
2	Ease to follow the exercise	3%	8%	4%	47%	38%
3	Exercise knowledge objectives accomplished	3%	0%	8%	28%	61%
4	Additional knowledge acquired	3%	3%	12%	50%	32%
5	Usefulness of switching	0%	0%	3%	31%	66%
6	Most valuable resource	58%	3%	31%	8%	0%
7	Learning usefulness of scale-model system	19%	0%	16%	39%	26%
8	Most important switching concept-element	15%	23%	0%	62%	0%
9	Satisfaction degree	3%	0%	8%	32%	57%

* 1–5, 9: A = Strongly disagree; B = Disagree; C = Neutral; D = Agree; E = Strongly agree

* 6: A = Teacher; B = Documentation; C = Simulation; D = Scale model; E = Other

* 7: A = Not important; B = Few important; C = Neutral; D = Important; E = Very important

* 9: A = Switching mechanism; B = Operation regions; C = Switching boundaries; D = Relation among switching elements; E = Other

VII. CONCLUSION

This paper has presented the stages of a step-by-step educational experiment to learn and understand key concepts in switching control. This experiment provides students with insight into switching-control characteristics and the strong connection between the nature of the control problem and the different components of the switching scheme. Also, it develops the skills of implementing a switching control system (including the multicontroller scheme, the switching mechanism, and a supervisory layer) and of applying switching-control strategies to nonlinear systems. Furthermore, the simulations and experiments performed help students to acquire a deep understanding of: 1) the way in which switching control can improve the performance of individual local controllers when control actions must be performed across the whole operating range, and 2) how a switching mechanism can improve a multicontroller scheme performance.

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