Hindawi
Mathematical Problems in Engineering
Volume 2017, Article ID 3597346, 12 pages
https://doi.org/10.1155/2017/3597346

Research Article

Fuzzy Supervisor Approach Design Based-Switching Controller for Pumping Station: Experimental Validation

Wael Chakchouk, Chiheb Ben Regaya, Abderrahmen Zaafouri, and Anis Sellami

Higher National Engineering School of Tunis (ENSIT), Laboratory of Industrial Systems Engineering and Renewable Energy (LISIER), University of Tunis, Taha Hussein Street, BP 56, Bab Menara, 1008 Tunis, Tunisia

Correspondence should be addressed to Wael Chakchouk; wael.chakchouk@ensit.rnu.tn

Received 16 June 2017; Revised 7 September 2017; Accepted 1 November 2017; Published 23 November 2017

Academic Editor: Stefan Balint

This paper proposes a discrete-time switching controller strategy for a hydraulic process pumping station. The proposed solution leads to improving control system performances with two tests: combination of Fuzzy-PD and PI controllers and Fuzzy-PID and PI controllers. The proposed design methodology is based on accurate model for pumping station (PS), which is developed in previous works using Fuzzy-C Means (FCM) algorithm. The control law design is based on switching control; a fuzzy supervisor manages the switching from one to another and regulates the rate of participation of each order, in order to satisfy various objectives of a stable pumping station like the asymptotic stability of the tracking error. To validate the proposed solution, experimental tests are made and analyzed. Compared to the conventional PI and fuzzy logic (FL) approaches, the results show that the switching controller allows exhibiting excellent transient response over a wide range of operating conditions and especially is easier to be implemented in practice.

1. Introduction

Nonlinear system modeling has been a subject of some interest in the field of control theory for many years. In this review, the material is presented which provides the relevant perspective of the subject area with regard to signal processing applications. Therefore, the biggest challenge to researchers is to find solutions to problems encountered in real applications; in our case it is the pumping station. It is a complex nonlinear and interconnected system; then to build a precise mathematical model of this system is difficult task because the mathematical solutions for this system are very complex and require enormous amounts of computation. Moreover, it contains many variables which are too vague to model. In order to build an accurate model for the pumping station system, several algorithms based on Takagi-Sugeno (T-S) fuzzy model [1–7] have been carried out recently to identify the parameters for "black-box" systems using input-output data sets, among them the Fuzzy-C Means (FCM) algorithm [8–16]. The latter is particularly the most effective technique that can be used in nonlinear systems identification.

It is applied in many fields such as image segmentation [17] and sensor networks [18]. For this, we have used FCM algorithm to find a mathematical model for pumping station.

Many control laws have been developed in literature for pumping station using different techniques. The authors of [19, 20] have used a proportional integral (PI) controller to drive the pumping station system. In [20, 21] the authors have applied a fuzzy logic control (FLC) to the same system. More recently, a hybrid controller based on PI and FLC controllers has been developed in [22]. However, those aforementioned works have the major drawbacks. In [19–23], the problems are higher steady state error, higher overshoot, and having unstable tracking performance.

To overcome those problems, in this paper a new methodology based on switching approach is proposed for Single-Input Multiple-Output (SIMO) discrete-time system.

The control scheme developed consists of a fuzzy supervisor managing the combination between two controllers in two tests: the first one is the combination of Fuzzy-PD and PI controllers [21], and the second deals with the combination of Fuzzy-PID and PI controllers.

In literature, combination of different techniques to obtain the best performances is widely used today. Wong et al. [24] proposed a combination of three methods: SMC, fuzzy logic control (FLC), and PI control. The resulting controller eliminates the chattering and the steady error introduced by the FLC. Lin and Chen [25] used genetic algorithms to optimize the mixing of SMC and FLC and hence to reduce chattering in the system. Barrero et al. [26] developed a FLC-based hybrid controller to manage the switching between a SMC and a Fuzzy-PI controller. Reference [27] developed a hybrid controller to manage the switching between fuzzy logic and PI controllers. Nevertheless, the above-mentioned works use a fixed combination or restrictive assumptions for the rapidity and the stability of the pumping station.

Based on the aforementioned works, the main contribution of this paper is to develop a discrete-time switching (hybrid) control applied for a water pumping station (Irrigation Station (IS)). It should be noticed that the mathematical model of IS is discrete-time linearized system described in [19]. The aim of this paper is to propose a fuzzy supervisor for switching combination between two controllers to overcome their disadvantages and to ensure the robustness and the stability of the closed loop system. The discrete-time switching control is based on the combination of the Fuzzy-PD or Fuzzy-PID with PI controllers. The developed method has the advantage of combining the performance of both controllers. A fuzzy supervisor manages the switching from one to another controller in order to resolve the tracking problem of pressure in pipe line and sprinklers. Then, the proposed switching control applied to the water pumping station is validated experimentally through MATLAB-Simulink (R2011b"7.13.0.564") environment and the dSpace DS1104 card based on real-time data acquisition control system.

This study is organized as follows: In Section 2, the mathematical model of pumping station is presented. In the next section, there exists presentation of different control laws (PI, Fuzzy-PD, and Fuzzy-PID). The switching control structure is designed and expressed in a suitable form. To demonstrate the various features of the proposed switching controller scheme, formulating switching controller problems, fuzzy logic supervisor, and the proposed approach, simulation results are given and compared to classical PI, Fuzzy-PD, and Fuzzy-PID controllers. The experimental validation of the switching control implemented to pumps is detailed in Section 4. Finally, Section 5 presents some concluding remarks.

2. Pumping Station Model

The pumping station model is developed in previous research. The authors [22, 28] used the hydraulic description model, which is based on the fluid mechanics laws, Navier-Stokes equations, and their simplification. However, in [19] they used the Takagi-Sugeno fuzzy model.

In this case, the above system may have the following form:

$$\begin{aligned} x_1(k+1) &= f_1^T(x_1) + g_1(x_1)\,x_2, \\ x_2(k+1) &= f_2^T(x_1,x_2) + g_2(x_1,x_2)\,u(k), \end{aligned} \tag{1}$$

where $[x_1\ x_2]^T$ represents the discrete state space vector and u is the input of system. The output y is chosen equal to x_1 and the reference signal y_r is assumed to be known and uniformly bounded. The linear numerical model is described by (1) using the fuzzy Takagi-Sugeno technique which is obtained by the following three steps [19]:

(1) Determination of premises parameters using the Fuzzy-C Means (FCM) algorithm

(2) Estimating consequential parameters using the Recursive Least Square (RLS)

(3) Model validation using the Root Mean Square Error (RMSE) and Variance Accounting For (VAF).

The IS is made up of two nonlinear systems which has the same inputs and different outputs, one of pressure and the other of flow, where each one is partitioned in three subsystems. The pressure and flow subsystems are described in previous works [19, 21] which are given by the following equations.

(i) For the pressure subsystems,

$$\begin{aligned} R_{p1} : y_{P1}(k) &= 1.0853 y_{p1}(k-1) - 0.1744 y_{p1}(k-2) \\ &\quad + 0.0570 u_1(k-1) \\ &\quad + 0.0318 u_1(k-2), \\ R_{p2} : y_{P2}(k) &= 1.0851 y_{p2}(k-1) - 0.1743 y_{p2}(k-2) \\ &\quad + 0.0565 u_2(k-1) \\ &\quad + 0.0320 u_2(k-2), \\ R_{p3} : y_{P3}(k) &= 1.0852 y_{p3}(k-1) - 0.1750 y_{p3}(k-2) \\ &\quad + 0.0560 u_3(k-1) \\ &\quad + 0.0315 u_3(k-2). \end{aligned} \tag{2}$$

(ii) For the flow subsystems,

$$\begin{aligned} R_{Q1} : y_{Q1}(k) &= 1.0853 y_{Q1}(k-1) - 0.1744 y_{Q1}(k-2) \\ &\quad + 1.4118 u_1(k-1) \\ &\quad - 1.31 u_1(k-2), \\ R_{Q2} : y_{Q2}(k) &= 1.0851 y_{Q2}(k-1) - 0.1743 y_{Q2}(k-2) \\ &\quad + 1.4116 u_2(k-1) \\ &\quad - 1.33 u_2(k-2), \\ R_{Q3} : y_{Q3}(k) &= 1.0852 y_{Q3}(k-1) - 0.1750 y_{Q3}(k-2) \\ &\quad + 1.4120 u_3(k-1) \\ &\quad - 1.31 u_3(k-2). \end{aligned} \tag{3}$$

For the total system identification, the rule for each subsystem (flow and pressure) can be calculated by the following equation [19, 21]:

$$y(k+1) = \frac{\sum_{i=1}^{c} \mu_{ik} \cdot (x(k)) \cdot y_i(k+1)}{\sum_{i=1}^{c} \mu_{ik} \cdot (x(k))}; \tag{4}$$

using (2), (3), and (4) the global rules are given by (5) and (6).

(i) For the pressure output,

$$\begin{aligned} R_{PG} : y_{PG}(k) &= 1.0851 y_p(k-1) - 0.1745 y_p(k-2) \\ &\quad + 0.0563 u(k-1) + 0.0317 u(k-2). \end{aligned} \tag{5}$$

(ii) For the flow output,

$$\begin{aligned} R_{QG} : y_{QG}(k) &= 1.0851 y_Q(k-1) - 0.1745 y_Q(k-2) \\ &\quad + 1.4116 u(k-1) - 1.32 u(k-2). \end{aligned} \tag{6}$$

Thus, the open loop transfer functions are

$$\begin{aligned} H_{\text{BOP}} &= \frac{0.05632 z + 0.0317}{z^2 - 1.0851 z + 0.1745}, \\ H_{\text{BOQ}} &= \frac{1.4116 z - 1.32}{z^2 - 1.0851 z + 0.1745}. \end{aligned} \tag{7}$$

The discrete state representation is given by [19, 21]

$$\begin{aligned} \begin{bmatrix} P_{k+1} \\ Q_{k+1} \end{bmatrix} &= \begin{bmatrix} 1.085 & -0.1745 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} P_k \\ Q_k \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} u(k), \\ y_k &= \begin{bmatrix} 0.0563 & 0.0317 \\ 1.412 & -1.32 \end{bmatrix} \begin{bmatrix} P_k \\ Q_k \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} u(k), \\ A &= \begin{bmatrix} 1.085 & -0.1745 \\ 1 & 0 \end{bmatrix}, \\ B &= \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \\ C &= \begin{bmatrix} 0.0563 & 0.0317 \\ 1.412 & -1.32 \end{bmatrix}. \end{aligned} \tag{8}$$

Based on Shannon theory, the sampling period T_s is chosen as 0.04 s.

3. Controls Used on the Pumping Station

This section defines the different controllers such as PI, Fuzzy-PD, Fuzzy-PID, and the switching between PI/Fuzzy-PD and PI/Fuzzy-PID.

3.1. PI Control Design. The block scheme of the pumping station controlled by a PI regulator as shown in Figure 1 is provided by LEROY-SOMMER. This controller ensures specific control for the pumps. The originators in the LEROY-SOMMER company choose the parameters of following adjustments $K_p = 0.5$ $T_i = 1$ m:

$$\frac{U(s)}{\varepsilon(s)} = K_p \left(1 + \frac{1}{T_i s}\right). \tag{9}$$

The form of discrete PI controller is given by

$$\begin{aligned} \frac{U(z)}{\varepsilon(z)} &= \frac{K_p(1 + T/T_i) - K_p z^{-1}}{1 - z^{-1}} = \frac{r_0 + r_1 z^{-1}}{1 - z^{-1}} \\ &= \frac{r_0 z + r_1}{z - 1}. \end{aligned} \tag{10}$$

Simulation results of PI controller are shown in Section 3.5.

Table 1: Inference matrix of the fuzzy controller.

	N	Z	P
N	PB	PS	NS
Z	PS	Z	NS
P	PS	NS	NB

3.2. Fuzzy-PD Control Design. The pumping station controlled by the fuzzy logic shown in Figure 2 [21] must be programmed through the tool "FUZZY" of MATLAB. Entries "and" are chosen of Gaussian form (bell) and the universe of speech for each one is divided into three sets: Z, P, and N. Thus, by using all the possible combinations, nine fuzzy rules were generated for five singletons on the level of the consequence part as shown in Table 1.

In the proposed method each input variable of the fuzzy logic controller has three Gaussian membership functions. The fuzzy sets used in the proposed method are as follows: N: Negative, P: Positive, and Z: Zero. Output variables have five membership functions as follows: NB: Negative Big, NS: Negative Small, Z: Zero, PB: Positive Big, and PS: Positive Small. The variation law of fuzzy controller is shown. The rules can be written in Table 1.

$$\begin{gathered} f(\varepsilon \text{ is } A) \text{ and } (\dot{\varepsilon} \text{ is } B) \\ \text{then } U_{cf} = S_i(\varepsilon, \dot{\varepsilon}). \end{gathered} \tag{11}$$

The discourse universe of output U_{cf} is decomposed in five fields. The method min-max is used for inferences system and the gravity centre method for the defuzzification step. Then the fuzzy controller can be written as follows:

$$\begin{aligned} S_i(\varepsilon, \dot{\varepsilon}) &= \min\left(\mu_A^i(\varepsilon), \mu_B^i(\dot{\varepsilon})\right), \\ U_{cfG} &= \max\left(S_i(\varepsilon, \dot{\varepsilon})\right). \end{aligned} \tag{12}$$

Simulation results of fuzzy controller are shown in Section 3.5.

3.3. Fuzzy-PID Control Design. The additive combination of proportional, integral, and derivative actions is called

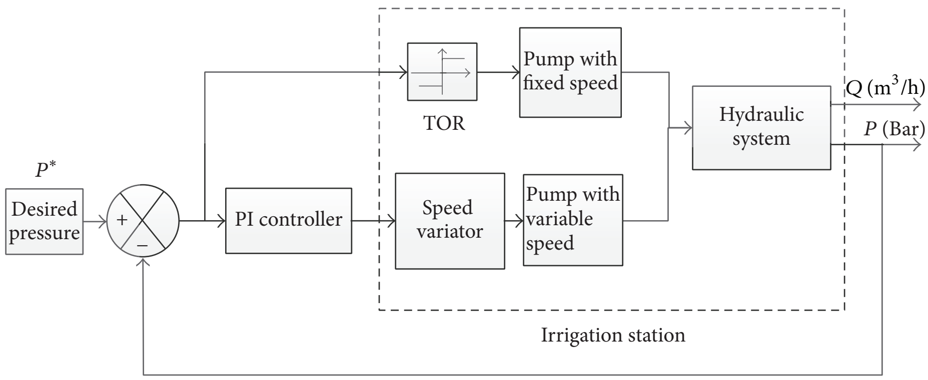

Figure 1: Block scheme of the pumping station controlled by PI regulator.

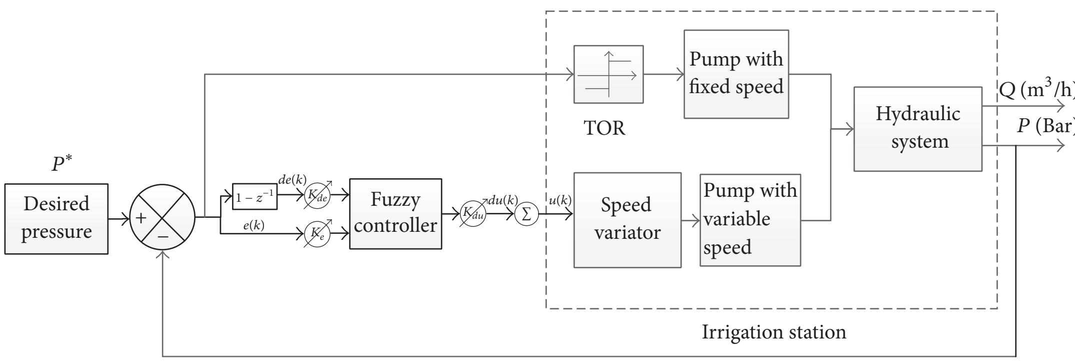

Figure 2: Block scheme of the controlled pumping station based on fuzzy logic.

proportional-integral-derivative action [29, 30]. These types of controllers have been widely used for industrial processes owing to their heuristic nature associated with simplicity and effectiveness for both linear and nonlinear systems. A parallel structure of Fuzzy-PID control systems is proposed in [29, 30] based on the parallel combination of Fuzzy-PI and PD controllers which shows its simplicity in determining the control rules and controller parameters. It is associated with a tuning method which is based on gain margin and phase margin specifications. The block diagram of a Fuzzy-PID control is shown in Figure 3. The input linguistic variables to the Fuzzy-PID controller are as follows: error ($e(k)$) and change in error ($e(k)$). Error and change in error are defined on the universe of discourse of −5 to 5. The fuzzy sets have the same structure as the Fuzzy-PD in Section 3.2.

The simulation results are illustrated in Figures 4 and 5 which present the pressure and the flow outputs of the proposed system based on switching technique, respectively.

The evolution of the pressure tracking error with Fuzzy-PID controller is given by Figure 4. From the output tracking errors, the proposed Fuzzy-PID method shows that the tracking error is smaller than 1%, which proves the tracking accuracy. The proposed design based on combination of Fuzzy-PI and PD controllers technique shows a better tracking performance and high efficiency.

3.4. Switching Control Synthesis. The solution presented in this paper consists in using simultaneously controllers 1 and 2 as illustrated in Figure 6. This solution has the advantage of combined performances of both controllers based on an appropriate switching algorithm described in Figure 7.

3.4.1. Fuzzy Supervisor. To ensure the more robustness of the closed loop system and a fast dynamic response with the best performance, a combination of the two previously defined controllers is made. This combination multiplexes the fuzzy logic control during the transient state and the PI control in steady state. The first command ensures a fast convergence of the system to steady state with insensitivity to external disturbances, while the second takes over steady state to ensure a more smooth and a minimal static error. To avoid a sudden transition from one controller to another, a gradual switching is used [31–34] which has the following form:

$$U_{\mathrm{HC}} = \alpha U_{\mathrm{FLC}} + (1-\alpha)\, U_{\mathrm{PIC}}, \tag{13}$$

where α is a weighting factor generated by a fuzzy supervisor. The rule base of the latter is constructed such that the output moves "to zero" when the system is far from the desired value, and "value 1" when the tracking error and its derivatives converge to zero [31, 32]. The main objective of fuzzy supervisor is to determine the weighting factor α, which gives the participation rate of each control signal.

The state space is partitioned in several regions using a Sugeno fuzzy system. Also, the product inference, the algebraic sum, and the singleton for the consequent-part are

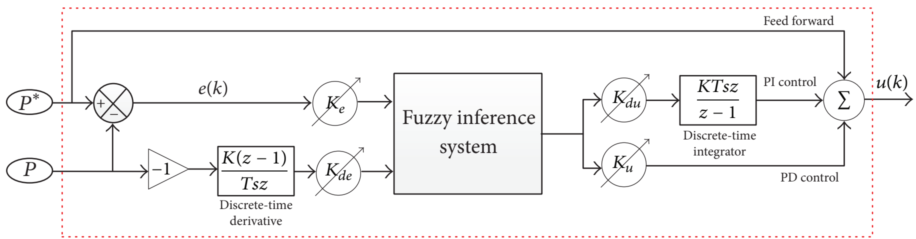

Figure 3: Fuzzy-PID controller block.

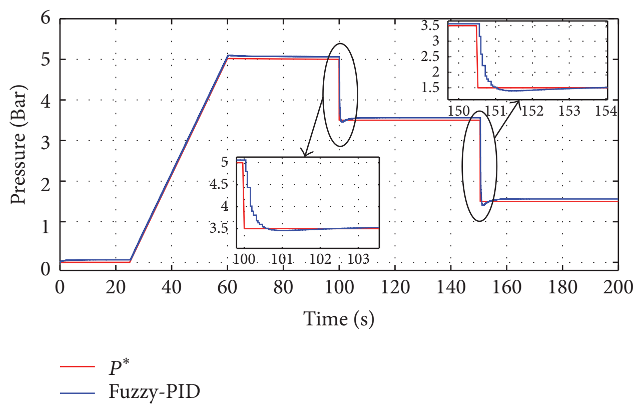

Figure 4: Pressure evolution of pumping station with Fuzzy-PID controller.

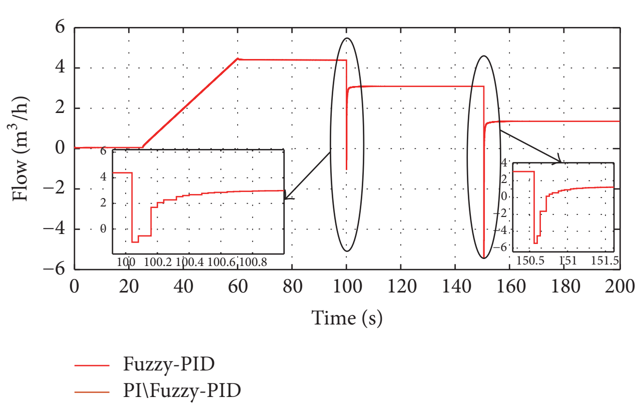

Figure 5: Pressure evolution of pumping station with Fuzzy-PID controller.

used to design fuzzy supervisor as shown in Figure 8. Hence, the fuzzy system output can be written as follows:

$$\alpha = \frac{\sum_{j=1}^{m} \alpha_j \prod_{i=1}^{n-1} \mu_{H_i^j}\left(e^{(i)}\right)}{\sum_{j=1}^{m} \prod_{i=1}^{n-1} \mu_{H_i^j}\left(e^{(i)}\right)}, \quad (14)$$

where H_i^j is a fuzzy set, $\mu_{H_i^j}$ is the membership degree of $e^{(i)}$ to H_i^j, α_j is a singleton, and m is the number of used fuzzy rules.

3.4.2. Simulation Results. The first test proposes a switching controller based on the combination between two conventional controllers: PI and Fuzzy-PD. In fact, the evolution of the pressure and the flow outputs are presented in Figures 9 and 10, respectively.

The second test presents a switching controller based on the combination between two controllers: conventional PI and Fuzzy-PID. The pressure and the flow outputs with PI/Fuzzy-PID controllers are given by Figures 11 and 12.

3.5. Comparative Study. In this section, a comparative study of all control laws applied for the pumping station is made.

The choice of the reference signal is rich on a vast time range, in which we find at the beginning a dead zone and then a ramp and a series of steps signals with different amplitude. This choice allows highlighting the effect of the control law in all operation points and studying the system robustness against the sudden changes of needed water level into sprinklers.

The obtained results ensure the pressure regulation because the response follows the given reference as illustrated in Figures 13 and 14. The response time and the static error related to the pressure output are summarized in Table 2. Table 3 presents the response time and the overshoot related to the flow output. The major drawback of this method of regulation resides primarily at the adaptation problem of the controller face to the external variations such as the extension of drain network, disturbance, and the slowness outputs response.

Note that a saturation was added in the control loop in order to limit the overshoot of flow which is motioned in the constructor document that does not exceed 8 m^3/h.

Apart from stability, the transient behaviour is another focus of attention for control systems design. There are several properties that can be used to evaluate the transient behaviour of a closed loop control system, for example, steady state accuracy, settling time, and overshoot [35].

Beyond these properties, more widely used criteria for quality of control (QoC) relate to the control error, which is defined as the difference between the setpoint $P^*(k)$ and the system outputs $P(k)$ and $Q(k)$. Some of these performance indices are given below in both continuous-time and discrete-time forms, where k_0 and k_f are the initial and final discrete-times of the evaluation period [35]. The quality of control criteria are given as follows.

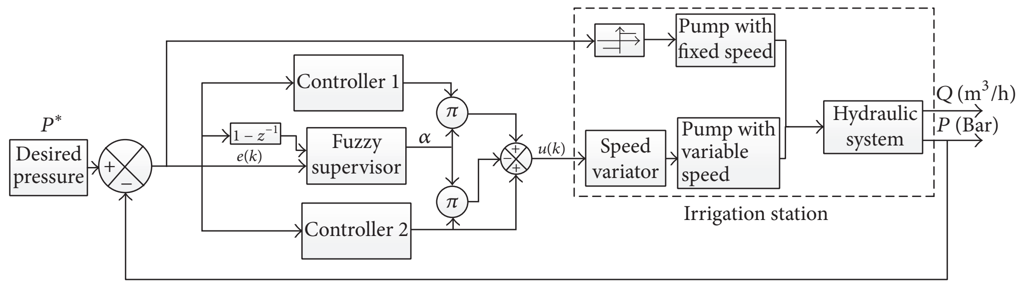

Figure 6: Bloc scheme using the switching controller technique.

Table 2: Response time and static error of all controllers for the pressure output.

	PI	Fuzzy-PD	Switch PI-Fuzzy-PD	Fuzzy-PID	Switch PI-Fuzzy-PID
Response time at ±5%	12.6 s	6.6 s	7 s	6.37 s	6.14 s
Static error of position (in Bar)	0.68	0.1	0.01	0.06	0.02

Table 3: Response time and overshoot of all controllers for the flow output.

	PI	Fuzzy-PD	Switch PI-Fuzzy-PD	Fuzzy-PID	Switch PI-Fuzzy-PID
Response time at ±5%	13.4 s	11.6 s	8 s	9 s	6 s
Overshoot in %	25.44%	58%	28.94%	30.56%	27.21%

(i) Integral of Absolute Error (IAE):

$$\mathrm{IAE} \approx \sum_{k=k_0}^{k_f} |e(k)| \approx \sum_{k=k_0}^{k_f} \left|P^*(k) - P(k)\right|. \tag{15}$$

(ii) Integral of Time-weighted Absolute Error (ITAE):

$$\mathrm{ITAE} \approx \sum_{k=k_0}^{k_f} k\,|e(k)| \approx \sum_{k=k_0}^{k_f} k\left|P^*(k) - P(k)\right|. \tag{16}$$

(iii) Integral of Square Error (ISE):

$$\mathrm{ISE} \approx \sum_{k=k_0}^{k_f} (e(k))^2 \approx \sum_{k=k_0}^{k_f} \left(P^*(k) - P(k)\right)^2. \tag{17}$$

(iv) Integral of Time-weighted Square Error (ITSE):

$$\mathrm{ITSE} \approx \sum_{k=k_0}^{k_f} k\,(e(k))^2 \approx \sum_{k=k_0}^{k_f} k\left(P^*(k) - P(k)\right)^2. \tag{18}$$

According to Figures 13 and 14 the ratio speed/power for both outputs (pressure and flow) of the studied system with switching control is higher than other controllers (PI, Fuzzy-PD, and Fuzzy-PID).

For pressure output, we notice that fuzzy supervisor approach takes the speed performance of Fuzzy-PD or Fuzzy-PID controllers and the smooth evolution of PI controller, so the switching controller eliminates the small oscillation in transient state for mixing PI/Fuzzy-PD controller.

The obtained results by switching controller show that this control strategy is able to limit the oscillation in transient state, without need of the saturation in flow output of pumping station with fuzzy controller (Fuzzy-PD or Fuzzy-PID).

Figure 14 shows the stable value of steady state (e.g., 4.83 m^3/h between $t = 60$ and $t = 100$), which ensured the saving of water use and the economy of electrical energy absorbed by the pumps to reach the pressure set point (5 bar) in the pipelines of the pumping station even in the sprinklers.

The quantitative comparison as shown in Tables 2, 3, and 4 reflects the switching of PI-Fuzzy-PD and PI-Fuzzy-PID which are better than single controllers as PI, Fuzzy-PD, and Fuzzy-PID.

4. Control Algorithm Validation

4.1. Experimental Bench Configuration. To check the performances of the proposed DABs controller, simulations and experimental tests were carried out based only on the estimation model. Operational algorithm of pumps and system regulation are shown in Figure 7. The scheme used for the experimental setup is shown in Figure 15.

The experimentation has been carried out using MATLAB-Simulink and dSpace $DS1104$ real-time controller board. This board contains a Motorola Power PC 603e model that operates at the speed of 250 MHz and a DSP ($TMS320F240$ – 20 MHz).

The developed experimental test bench of the electrical control cabinet is shown in Figure 16. In the cabinet configuration, A3, A4, and A5 blocks represent, respectively, flow sensor and two pressure sensors. The electrical regulator pressure card is described by A2 block. The A1

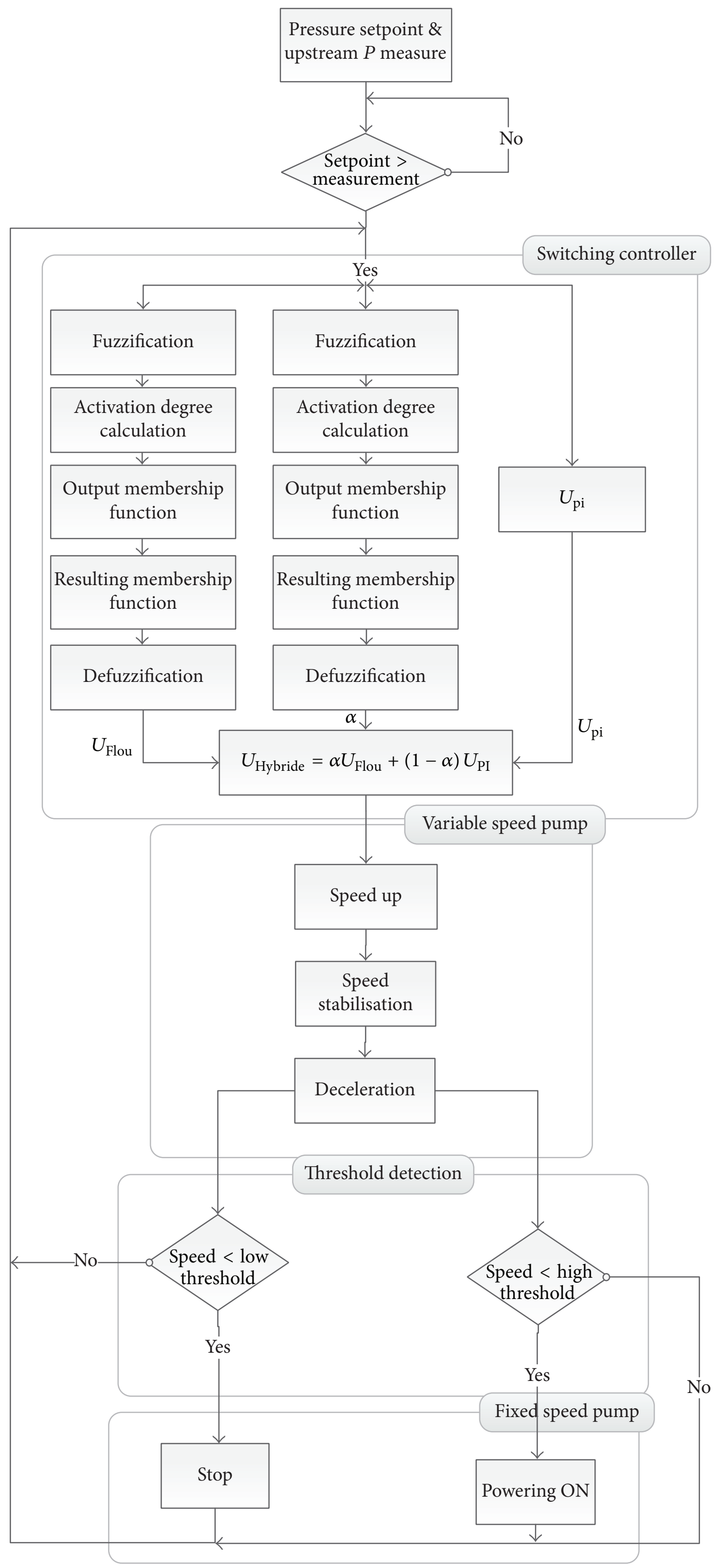

Figure 7: Switching control algorithm.

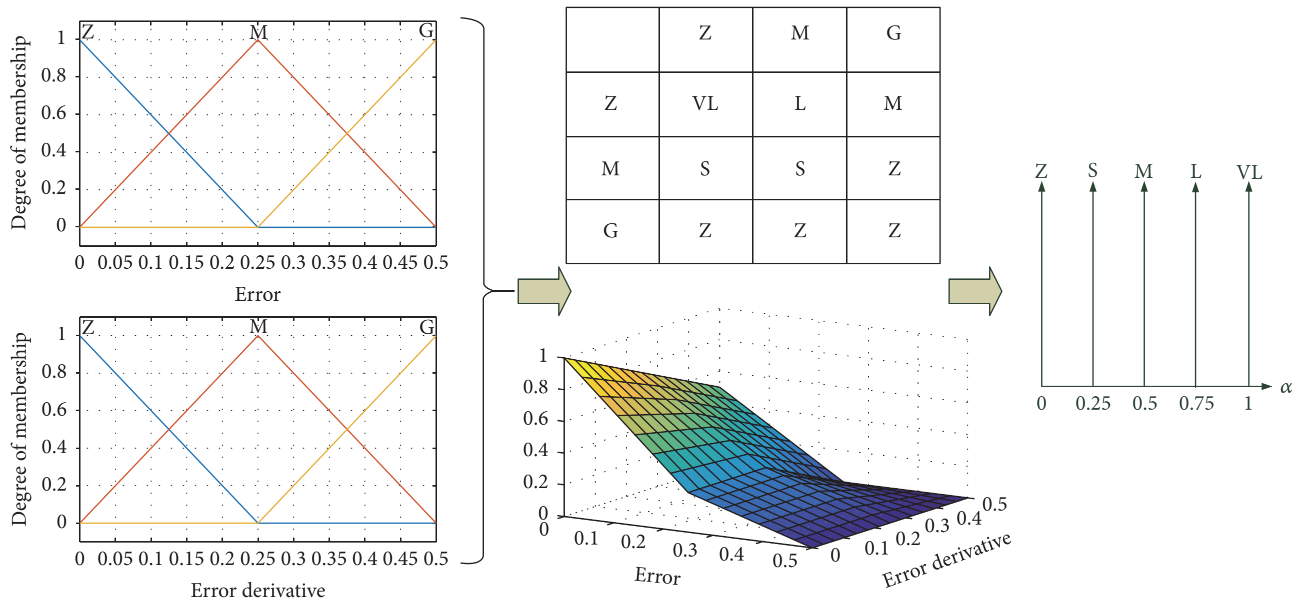

Figure 8: Supervisory fuzzy inference machine.

Table 4: Quality of control criteria of all controllers.

	PI	Fuzzy-PD	Switch PI-Fuzzy-PD	Fuzzy-PID	Switch PI-Fuzzy-PID
IAE	0.943	0.2256	0.115	0.11	0.108
ITAE	188.6	45.11	13.109	11.87	9.73
ISE	0.8893	0.05088	$2.416e-3$	$9.27e-4$	$7.415e-4$
ITSE	177.9	10.18	4.832	3.774	3.027

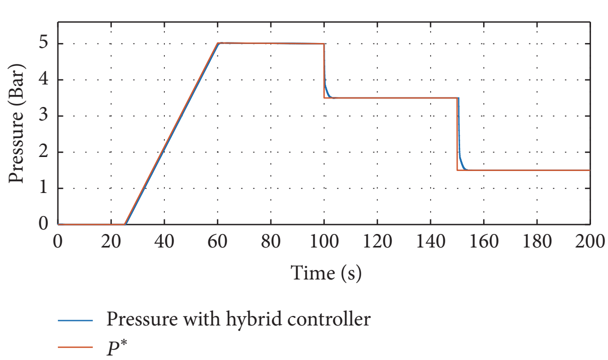

Figure 9: Pressure output with PI-Fuzzy-PD switching controller.

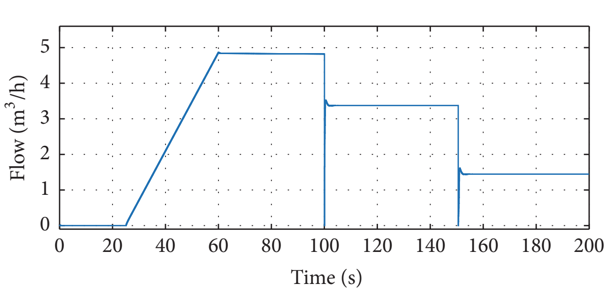

Figure 10: Flow output with PI-Fuzzy-PD switching controller.

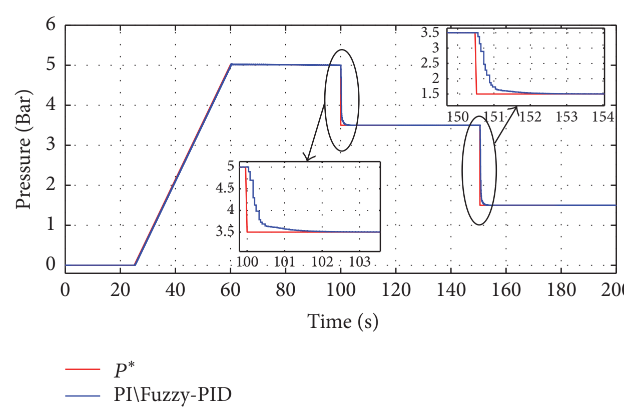

Figure 11: Pressure output with PI-Fuzzy-PID switching controller.

block represents the speed variator. In addition, the cabinet configuration contains two motor-pumps: fixed speed motor-pump of 1.1 kW rated power and variable speed motor-pump of 1.5 kW rated power. Table 5 summarizes the characteristics of the two motor-pumps.

The practical process is controlled as follows:

(1) Measure the pressure (Bar) from A5 block of the station.

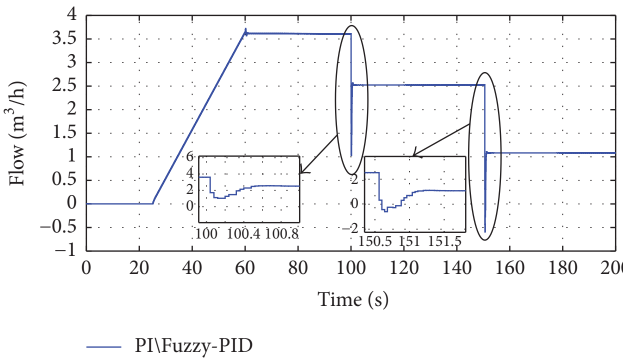

FIGURE 12: Flow output with PI-Fuzzy-PID switching controller.

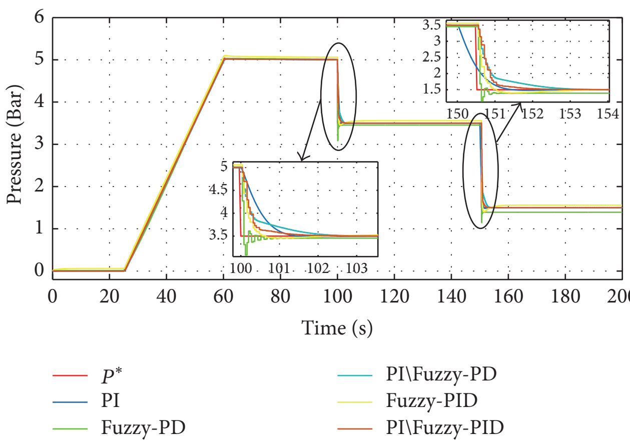

FIGURE 13: Performance results of different control laws for pressure output.

TABLE 5: Pumps parameters.

Variable speed pump	Fixed speed pump
Coupling star 400 V/50 Hz	Coupling star 400 V–50 Hz
Nn_v = 2870 tr/min	Nn_f = 2835 tr/min
$\cos_v(\varphi)$ = 0,81	$\cos_f(\varphi)$ = 0,84
In_v = 3,3 A	In_f = 2,5 A
Power: 1,5 kW	Power: 1,1 kW
H max = 80 m	H max = 58 m

Nn represents rated speed, $\cos(\varphi)$ is the power factor, In is the rated current, and H max represents the maximum height of pumps.

(2) Send this information to the controller board of the dSpace through ADC, 16-bit input.

(3) In another side, we load the parameters of the BS controller in real-time simulation using MATLAB-Simulink software, with the presence of the dSpace card *DS*1104 plugged in a personal computer.

A PCI bus cable makes the connection between the *DS*1104 cards and the controller board. The new control set point is calculated in dSpace (closed loop system with PI controller). The *DS*1104 sends the order to the pumping station by one of the connectors, DAC, in the controller board. The practical dynamics of IS outputs are extracted from the control Desk software which are given in Figures 17 and 18.

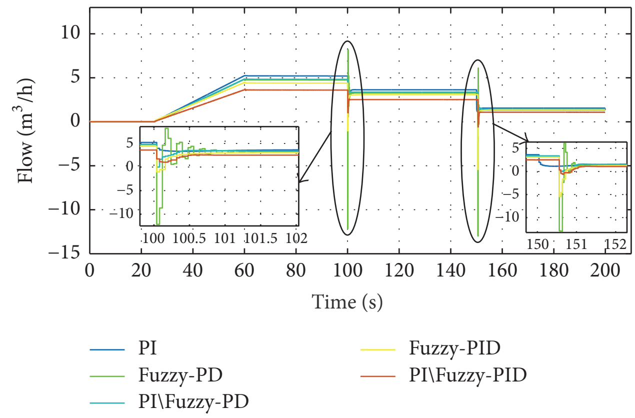

FIGURE 14: Flow performance results of different control laws for pressure output.

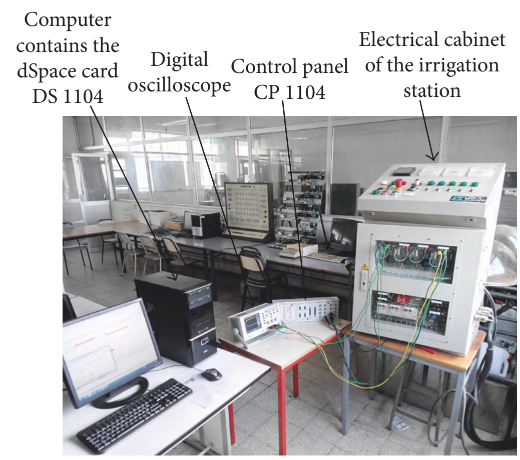

FIGURE 15: View of the experimental test system.

4.2. Experimental Results. The first test proposes an experimental validation result of switching controller based on the combination between two conventional controllers: PI and Fuzzy-PD. In fact, the real evolution of the pressure and the flow outputs are presented in Figures 17 and 18, respectively.

In Figure 17, it is can be noted that the pressure evolution curve (in red color) can converge towards the reference pressure. Figure 18 shows that the practical evolution of flow output is similar to the simulation results, which converge to 4.8 m^3/h.

The flow response has a relation with the absorbed energy by the pumps units. It can be noted that the proposed switching control strategy can guarantee at the same time the saving of water use, and the economy of electrical energy absorbed by the pumps to reach the reference pressure in the pipelines of the pumping station even in the sprinklers.

The second test presents an experimental validation of switching controller based on the combination between two controllers: conventional PI and Fuzzy-PID. The pressure and

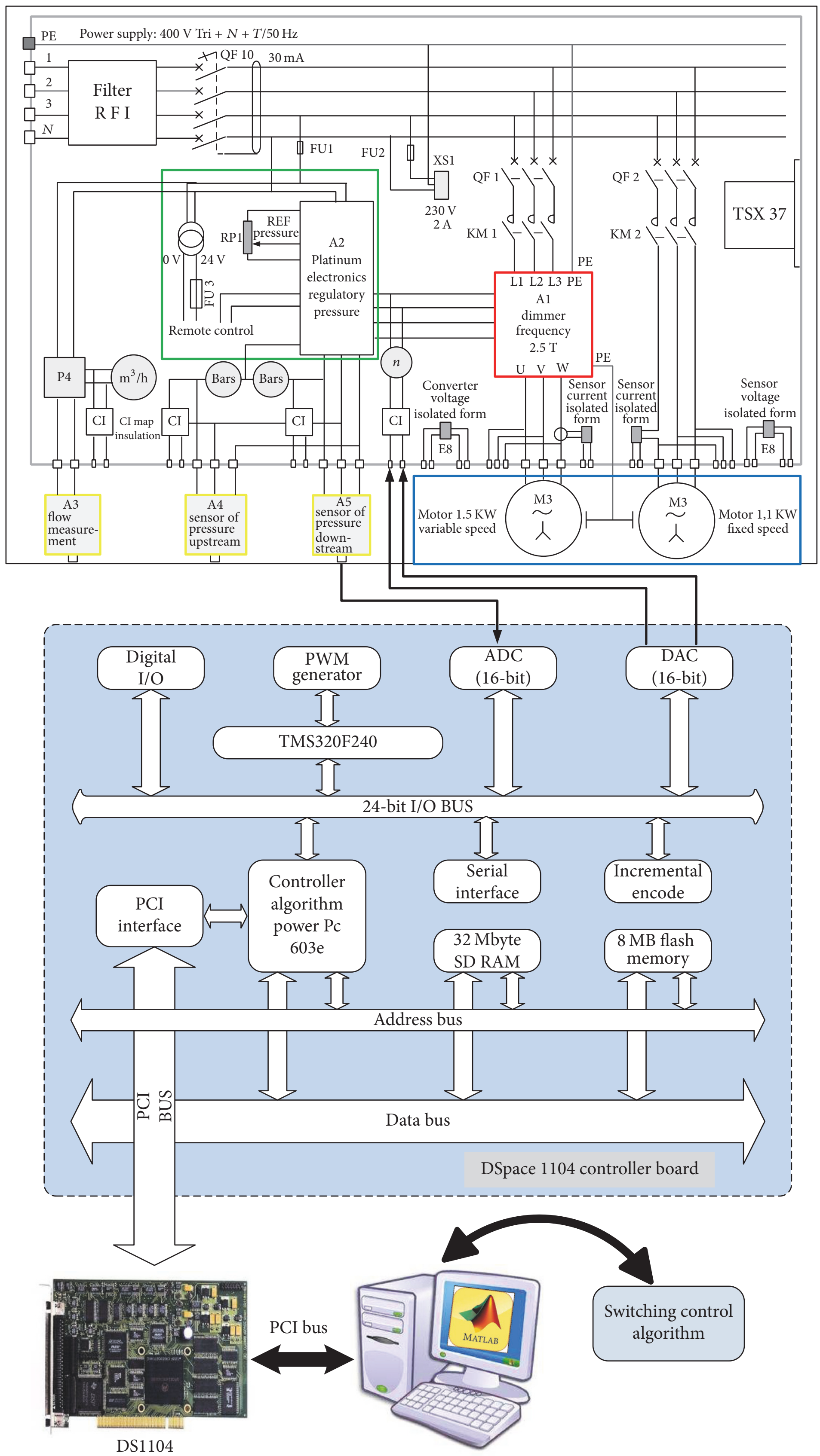

Figure 16: Experimental testing configuration.

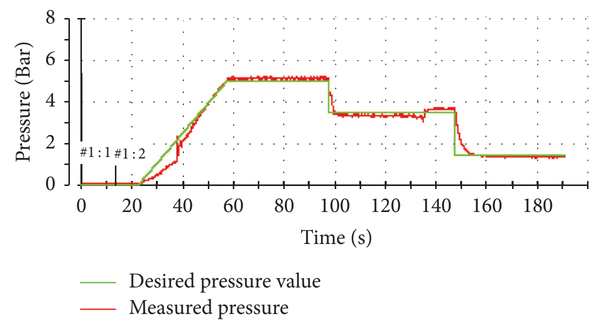

Figure 17: First test: experimental result of pressure with trapezoidal reference.

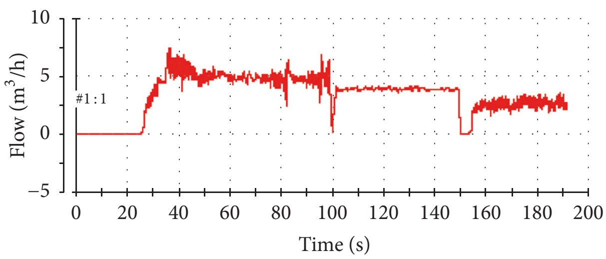

Figure 18: First test: experimental result of flow.

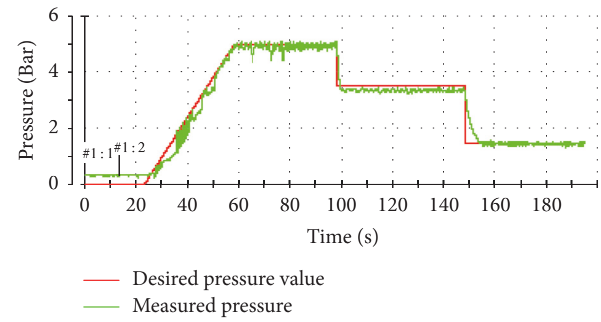

Figure 19: Second test: experimental result of pressure with trapezoidal reference.

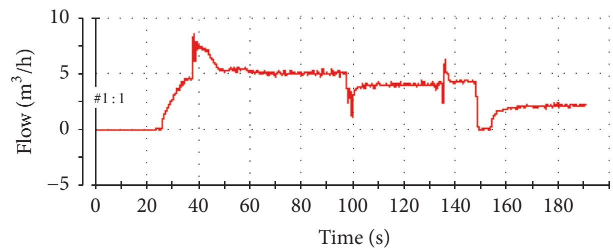

Figure 20: Second test: experimental result of flow.

the flow outputs with PI/Fuzzy-PID controllers are given by Figures 19 and 20.

The digital simulation and experimental results show clearly the improvement in performance of the proposed switching controller algorithm. Similarly, in Figure 19, the tracking error between the reference and the real pressure output reached the objective of the experimental validation and confirmed the simulation results.

According to the obtained results, the switching controller PI-Fuzzy-PID has a good performance in pressure output while the switching controller PI-Fuzzy-PD presents a good performance in flow output. The switching PI-Fuzzy-PD controller has a benefit in terms of experimental implementation as convergence time and implementation simplicity compared to switching PI-Fuzzy-PID controller.

5. Conclusion

Performances of a developed method for high-performance pumps pressure control based on switching technique that achieves global asymptotic pressure tracking outputs of a pumping station are presented. The elaborated switching control proves a good effectiveness and a simplicity compared to other controllers. After having developed the technical aspects of the switching controller using fuzzy supervisor, the complete control scheme of the pumping station incorporating the proposed controller experimentally was implemented using a digital signal processor board *DS*1104. The proposed switching controller gave satisfactory results in terms of pressure reference tracking and minimization of the response time of pressure and flow, which show the effectiveness of control for this kind of controller of pumping station. Based on the obtained results, it can be concluded that the research into the switching technique has been very successful and can be implemented in any pumping station, which can increase the performance of pumping stations and will be the objective of other research.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] S. Vaidyanathan and A. T. Azar, “Takagi-Sugeno fuzzy logic controller for Liu-Chen four-scroll chaotic system,” *International Journal of Intelligent Engineering Informatics*, vol. 4, no. 2, pp. 135–150, 2016.

[2] D. Lee, Y. H. Joo, and I.-H. Ra, “Local stability and local stabilization of discrete-time T–S fuzzy systems with time-delay,” *International Journal of Control, Automation, and Systems*, vol. 14, no. 1, pp. 29–38, 2016.

[3] T. Wang, Y. F. Zhang, J. B. Qiu, and H. J. Gao, “Adaptive fuzzy backstepping control for a class of nonlinear systems with sampled and delayed measurements,” *IEEE Transactions on Fuzzy Systems*, vol. 23, no. 2, pp. 302–312, 2015.

[4] T. Wang, J. Qiu, S. Fu, and W. Ji, “Distributed Fuzzy H_∞ filtering for nonlinear multirate networked double-layer industrial processes,” *IEEE Transactions on Industrial Electronics*, vol. 64, no. 6, pp. 5203–5211, 2017.

[5] T. Takagi and M. Sugeno, “Fuzzy identification of systems and its applications to modeling and control,” *IEEE Transactions on Systems, Man, and Cybernetics*, vol. 15, no. 1, pp. 116–132, 1985.

[6] T. Wang, J. Qiu, and H. Gao, “Modeling the behavioral substrates of associate learning and memory: adaptive neural

models," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 21, no. 3, pp. 510–520, 1991.

[7] J. Qiu, S. Ding, H. Gao, and S. Yin, "Fuzzy-model-based reliable static output feedback H-infinity control of nonlinear hyperbolic PDE systems," *IEEE Transactions on Fuzzy Systems*, vol. 24, no. 2, pp. 388–400, 2016.

[8] V. H. Grisales, A. Gauthier, and G. Roux, "Fuzzy optimal control design for discrete affine takagi-sugeno fuzzy models: application to a biotechnological process," in *Proceedings of the IEEE World Congress on Computational Intelligence (WCCI '06)*, pp. 2369–2376, Vancouver, BC, Canada, July 2006.

[9] J. B. Machado, R. J. G. B. Campello, and W. C. Amaral, "Takagi-Sugeno fuzzy models in the framework of orthonormal basis functions," *IEEE Transactions on Cybernetics*, vol. 43, no. 3, pp. 858–870, 2013.

[10] W.-S. Jang, H.-I. Kang, B.-H. Lee, K. I. Kim, D.-I. Shin, and S.-C. Kim, "Optimized fuzzy clustering by predator prey particle swarm optimization," in *Proceedings of the IEEE Congress on Evolutionary Computation (CEC '07)*, pp. 3232–3238, Singapore, Singapore, September 2007.

[11] F. Liu, P. Lu, J. Pan, and R. Pei, "Improved fuzzy identification method based on Hough transformation and fuzzy clustering," *Journal of Systems Engineering and Electronics*, vol. 15, no. 3, pp. 257–261, 2004.

[12] C.-F. Juang, C.-M. Hsiao, and C.-H. Hsu, "Hierarchical cluster-based multispecies particle-swarm optimization for fuzzy-system optimization," *IEEE Transactions on Fuzzy Systems*, vol. 18, no. 1, pp. 14–26, 2010.

[13] N. Zahid, O. Abouelala, M. Limouri, and A. Essaid, "Fuzzy clustering based on K-nearest-neighbours rule," *Fuzzy Sets and Systems*, vol. 120, no. 2, pp. 239–247, 2001.

[14] E. Giusti and S. Marsili-Libelli, "A fuzzy decision support system for irrigation and water conservation in agriculture," *Environmental Modeling and Software*, vol. 63, pp. 73–86, 2015.

[15] J. Chrouta, A. Zaafouri, and M. Jemli, "An improved heterogeneous multi-swarm PSO algorithm to generate an optimal T-S fuzzy model of a hydraulic process," *Transactions of the Institute of Measurement and Control*, vol. 15, no. 1, Article ID 014233121769634, pp. 1–15, 2017.

[16] M. Soltani, A. Chaari, and F. Ben Hmida, "A novel fuzzy c-regression model algorithm using a new error measure and particle swarm optimization," *International Journal of Applied Mathematics and Computer Science*, vol. 22, no. 3, pp. 617–628, 2012.

[17] J. Qin, W. Fu, H. Gao, and W. X. Zheng, "Distributed k-means algorithm and fuzzy c-means algorithm for sensor networks based on multiagent consensus theory," *IEEE Transactions on Cybernetics*, vol. 47, no. 3, pp. 772–783, 2017.

[18] R. Meena Prakash and R. Shantha Selva Kumari, "Spatial fuzzy c means and expectation maximization algorithms with bias correction for segmentation of MR brain images," *Journal of Medical Systems*, vol. 41, article 15, 2017.

[19] W. Chakchouk, A. Zaafouri, and A. Zaafouri, "Modeling, identification and control of irrigation station with sprinkling: Takagi-Sugeno approach," in *Complex System Modelling and Control Through Intelligent Soft Computations*, vol. 319 of *Studies in Fuzziness and Soft Computing*, pp. 469–499, Springer, 2015.

[20] W. Chakchouk, C. Ben Regaya, A. Zaafouri, and A. Sallami, "An improved fuzzy logic control of irrigation station," in *Proceedings of the International Conference on Control, Decision and Information Technologies (CoDIT '17)*, Barcelona, Spain, April 2017.

[21] W. Chakchouk, A. Zaafouri, and A. Sallami, "Control and modelling using Takagi-Sugeno fuzzy logic of irrigation station by sprinkling," *World Applied Sciences Journal*, vol. 29, no. 10, pp. 1251–1260, 2014.

[22] M. R. Mejri, A. Zaafouri, and A. Chaari, "Hybrid control of a station of irrigation by sprinkling," *International Journal of Engineering and Innovative Technology*, vol. 3, no. 1, pp. 9–17, 2013.

[23] W. Chakchouk, A. Zaafouri, and A. Sallami, "Hybrid control of a station of irrigation by sprinkling: fuzzy supervisor approach," in *Proceedings of the 4th International Conference on Systems and Control (ICSC '15)*, pp. 43–49, Sousse, Tunisia, April 2015.

[24] L. Wong, F. H. Leung, and P. K. Tam, "Combination of sliding mode controller and pi controller using fuzzy logic controller," in *Proceedings of the IEEE World Congress on Computational Intelligence*, Anchorage, Alaska, USA, May 1998.

[25] S.-C. Lin and Y.-Y. Chen, "A GA-based fuzzy controller with sliding mode," in *Proceedings of the Fuzzy Systems, 1995. International Joint Conference of the Fourth IEEE International Conference on Fuzzy Systems and The Second International Fuzzy Engineering Symposium*, Yokohama, Japan, March 1995.

[26] F. Barrero, A. González, A. Torralba, E. Galván, and L. G. Franquelo, "Speed control of induction motors using a novel fuzzy sliding-mode structure," *IEEE Transactions on Fuzzy Systems*, vol. 10, no. 3, pp. 375–383, 2002.

[27] M. R. Mejri, A. Zaafouri, and A. Chaari, "Identification and hybrid control of astation of irrigation by sprinkling," in *Proceedings of the 14th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA '13)*, pp. 1–5, Sousse, Tunisia, December 2013.

[28] J. Chrouta, A. Zaafouri, M. Jemli, and W. Chakchouk, "Modeling and stabilization of nonlinear systems using PDC approach," *World Applied Sciences Journal*, vol. 32, no. 10, pp. 1742–1749, 2014.

[29] J. Jantzen, *Tuning of Fuzzy PID Controllers*, Technical University of Denmark, Department of Automation.

[30] J.-X. Xu, C.-C. Hang, and C. Liu, "Parallel structure and tuning of a fuzzy PID controller," *Automatica*, vol. 36, no. 5, pp. 673–684, 2000.

[31] N. Essounbouli, A. Hamzaoui, and J. Zaytoon, "A supervisory robust adaptive fuzzy controller," in *Proceedings of the 15th Triennial World Congress*, pp. 157–162, Barcelona, Spain, July 2002.

[32] N. Essounbouli, A. Hamzaoui, and N. Manamanni, "Fuzzy supervisor for combining sliding mode control and h_∞ control," in *International Fuzzy Systems Association World Congress*, vol. 2715 of *Lecture Notes in Computer Science book*, pp. 466–473, Springer, Berlin, Germany, 2003.

[33] N. Essounbouli, N. Manamanni, A. Hamzaoui, and J. Zaytoon, "Synthesis of switching controllers: a fuzzy supervisor approach," *Nonlinear Analysis. Theory, Methods & Applications*, vol. 65, no. 9, pp. 1689–1704, 2006.

[34] N. Essounbouli, A. Hamzaoui, and J. Zaytoon, "Fuzzy sliding mode control for a class of non-linear continuous systems," *International Journal of Computer Applications in Technology*, vol. 27, no. 2-3, pp. 174–182, 2006.

[35] F. Xia and Y.-x. Sun, *Control and Scheduling Codesign: Flexible Resource Management in Real-Time Control Systems*, Advanced Topics in Science and Technology in China, Springer, 2008.