A Method for Improving the Robustness of PID Control

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***Abstract*—In this paper, an effective method is proposed for robust proportional–integral–derivative (PID) control that is easily implementable on commonly used equipment such as programmable logic controller (PLC) and programmable automation controller (PAC). The method is based on a two-loop model following control (MFC) system containing a nominal model of the controlled plant and two PID controllers. Basic features exhibited by the MFC structure are presented, and a technique to tune both component controllers is given. The proposed structures have been implemented in a programmable logic controller and tested on control plants with perturbed parameters. Also, the proposed control system has been checked for its performance in cases when the operation of PID controllers is based on fuzzy logic. Tuning rules for the fuzzy controllers in the presented MFC system have been proposed. Results of tests lend support to the view that the proposed control structures may find wide application to robust control of plants with time-varying parameters.**

***Index Terms*—Fuzzy control, model following control, proportional–integral–derivative (PID) control, robustness.**

I. Introduction

THE proportional–integral–derivative (PID) control algorithm, well proven in practice, still arouses considerable interest. Development of digital technology, progress in control theory, and identification have resulted in an increase in publications devoted to new theoretical results and technical solutions. This has been summarized in a survey paper [1]. Recently, a number of books dealing with PID control, e.g., [2]–[4], and a number of important papers [5]–[10] have appeared. This justifies the need for seeking new original solutions in the PID area, especially control algorithms being resistant to varying process parameters and easy to implement. Also, the use of fuzzy PID, the guiding rules for robust tuning of which are sought for, is encountered in the literature [11]. One of the well-known methods for PID robust design is the method based on the amplitude/phase margin approach. Although having been used for many years [5], [12], [13], among others, for processes with uncertain parameters, yet this approach has proved itself as being quite complicated for PID design [2].

In this paper, a simple method to improve the robustness of PID control is proposed. It has been assumed that the method should be easy to implement; therefore, provision is made for the employment of typical software library modules for process automation. The increase in robustness has been achieved using a two-loop model following control (MFC) system [14]. The MFC structure is noted for its simplicity and relatively high robustness to disturbances and stable perturbations. However, in spite of these advantages, MFC is not sufficiently reflected in the literature. Some papers report the use of MFC systems [15]–[19], another one deals with the properties of MFC [20]. Papers are encountered where the discussion is based on the state variable approach with the assumption that the process state vector is to follow the model state vector [21], [22], and also papers where the system representation is given by the transfer function [23], [24]. Such description makes a comparison of the properties of the MFC structure with those of the classic single-loop control structure much easier [18], [24]–[27].

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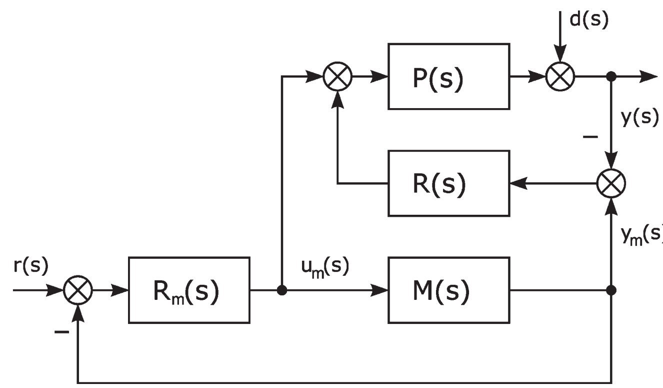

Fig. 1. MFC control structure.

II. Essential Properties of MFC Structure

The MFC structure shown in Fig. 1 can be regarded as a part of a more general class of systems called model-based control. The essential component of the plant input signal in the MFC structure is generated in an auxiliary control system containing a model of the plant $M(s)$ and its controller $R_m(s)$ in the feedback loop.

It means that the output of the model controller $R_m(s)$ acts on the input of the actual process plant. The second control loop of the MFC structure contains the auxiliary controller $R(s)$ and the actual process $P(s)$ disturbed by the signal $d(s)$, where the difference between the plant output $y(s)$ and the model output $y_m(s)$ is processed. Thus, the summed result of actions of both controllers, i.e., $R(s)$ and $R_m(s)$, excites the input of the actual plant $P(s)$. Note that for $R(s) = R_m(s)$ the MFC structure is equivalent to the classic single-loop feedback system.

Features exhibited by the MFC structure have been discussed in [24] and [27] in detail. Here, we shall dwell briefly on the main properties displayed by MFC. In order to evaluate the robustness of the MFC structure, some assumptions with respect to the process and its nominal model relation should be made. There are many reasons responsible for the presence of model uncertainties (errors in identification, errors in modeling, deliberate model simplification, process nonlinearities, fluctuations and variations of process parameters, etc.). Therefore, let the process model be given by

$$M(s) = M_0(s)e^{-sL} \tag{1}$$

and interrelated with the actual process $P(s)$ by

$$P(s) = M(s)\left[1 + \Delta(s)\right] \tag{2}$$

where $\Delta(s)$ denotes perturbations. From Fig. 1, it follows that

$$\begin{aligned} y(s) = y_m(s)\left[e^{-sL} + \frac{1 - e^{-sL} + \Delta(s)}{1 + R(s)M_0(s)\left[1+\Delta(s)\right]e^{-sL}}\right] \\ + \frac{d(s)}{1 + R(s)M_0(s)\left[1+\Delta(s)\right]e^{-sL}} \end{aligned} \tag{3}$$

where

$$y_m(s) = r(s)\frac{R_m(s)M_0(s)}{1 + R_m(s)M_0(s)}. \tag{4}$$

If the process delay $L = 0$, (3) reduces to

$$\begin{aligned} y(s) = y_m(s)\left[1 + \frac{\Delta(s)}{1 + R(s)M(s)\left[1+\Delta(s)\right]}\right] \\ + \frac{d(s)}{1 + R(s)M(s)\left[1+\Delta(s)\right]}. \end{aligned} \tag{5}$$

From (4) and (5), it may be easily noted that the relationship

$$y(s) \approx y_m(s) + \frac{d(s)}{1 + R(s)M(s)\left[1+\Delta(s)\right]} \tag{6}$$

holds only if the condition $|R(s)M(s)| > 1$ is fulfilled. If so, the follow-up error $y(s) - y_m(s)$ is almost independent of perturbations $\Delta(s)$, and moreover, disturbances $d(s)$ are suppressed according to the design of the auxiliary controller $R(s)$. Hence, the MFC structure exhibits the same advantageous properties as those of a two-degrees-of-freedom (2DOF) control [18].

By comparison, for the classic control structure with only one controller tuned to the process model but used to a perturbed and disturbed process, the following relationship holds:

$$\begin{aligned} y_{cl}(s) &= r(s)\frac{R_m(s)P(s)}{1 + R_m(s)P(s)} + d(s)\frac{1}{1 + R_m(s)P(s)} \\ &= y_m(s)\left[1 + \frac{\Delta(s)}{1 + R_m(s)M(s)\left[1+\Delta(s)\right]}\right] \\ &\quad + \frac{d(s)}{1 + R_m(s)M(s)\left[1+\Delta(s)\right]}. \end{aligned} \tag{7}$$

The basic factor that differentiates the MFC structure from the classic feedback structure is the disturbance sensitivity $S_d(s)$. From (4) and (6), it follows that $S_r(s) + S_d(s) \neq 1$ holds true for MFC systems, as for 2DOF systems. Here, $S_r(s)$ is the input sensitivity and $S_d(s)$ is the disturbance sensitivity [23], [27].

III. Design of the Model and Auxiliary Controllers

It should be emphasized that the R_m controller, according to (4), is associated with y_m only while the corrective controller R plays a crucial role in suppressing perturbations and disturbances [see (6)].

As may be inferred from Fig. 1, the model controller R_m plays a dual role in the MFC structure from the viewpoint of the auxiliary controller R. First, the R_m controller filters the reference signal of R, which has a favorable effect on transients in the process-containing loop, like in 2DOF systems. Due to the smoothening by the $R_m M$ control loop reference signal, the auxiliary controller R operates under much easier conditions. Second, the model controller R_m assists the auxiliary controller R in that it produces an additional process input u_m.

From what has been said, it might be assumed that the auxiliary controller may be tuned for a smaller stability margin or for a greater overshoot than controllers in simple single-loop control systems.

It may also be noted that the MFC structure offers an effective solution for an unknown delay-affected process control through a delay-free model in case the unknown time delay is of limited value [27].

As shown in [24], the influence of disturbances and perturbations on the process output is weaker, the greater is the transfer function magnitude of the R controller than that of the R_m controller, i.e.,

$$|R(j\omega)| > |R_m(j\omega)|, \qquad \omega \in [0, \infty). \tag{8}$$

The inequality (8) is restricted by stability conditions determined by roots of the equation

$$1 + R(s)M(s)\left[1 + \Delta(s)\right] = 0. \tag{9}$$

Hence, a general design directive can be adopted here: $|R_m|$ is bounded below by sufficiently good reference tracking conditions [see (4)] and $|R|$ is bounded above by stability conditions (9). At the same time, the inequality (8) should be as strong as possible.

It can also be shown that if the parameters of the controller R are chosen in compliance with the above-mentioned rules, then the range of admissible perturbations $\Delta(s)$ for the MFC structure is wider in comparison to the range obtained for the classic single-loop structure. As follows from [24], for the classic single-loop control structure containing the controller $R_m(s)$, the following inequality defining the admissible stable perturbations may be obtained, i.e.,

$$|\Delta_{cl}(s)| < \frac{|1 + R_m(s)M(s)|}{|R_m(s)M(s)|} \tag{10}$$

which should be fulfilled for all ω with $s = j\omega$. Correspondingly, the calculations made for the MFC structure yield

$$|\Delta_{\mathrm{MFC}}(s)| < \frac{|1 + R(s)M(s)|}{|R_m(s)M(s)|}. \tag{11}$$

It may be easily noted that the fulfilled condition (8) results in the inequality

$$|\Delta_{cl}(s)|_{\max} < |\Delta_{\mathrm{MFC}}(s)|_{\max} \tag{12}$$

hence, MFC provides higher robustness to perturbations.

With general directives for designing MFC controllers in mind, any known controller tuning technique in principle may be employed here. For example, one of them is that based on the Nyquist stability criterion [12], [13], [26]. In such a case, for the perturbed open-loop system containing the process (2) and the controller $C(s)$ to be designed, we have

$$K_{\mathrm{per}}(j\omega) = C(j\omega)M_0(j\omega)e^{-j\omega L}\left[1 + \Delta(j\omega)\right]. \tag{13}$$

If the process perturbations are bounded, i.e., they are subject to the condition

$$|\Delta(j\omega)| \le \Delta < 1, \qquad \omega \in [0, \infty) \tag{14}$$

the following inequality holds true:

$$1 - \Delta \le |1 + \Delta(j\omega)| \le 1 + \Delta \tag{15}$$

and also the phase $\varphi\Delta(\omega)$ of the expression $\Delta(j\omega)$ fulfills the inequality

$$-A_\Delta \le \varphi_\Delta \le A_\Delta, \qquad A_\Delta = \arctan\frac{\Delta}{\sqrt{1 - \Delta^2}} \tag{16}$$

where A_Δ is the designated phase margin.

This is illustrated in Fig. 2, where the $1 + \Delta(j\omega)$ vector and $K_{\mathrm{nom}}(j\omega) = R_m(j\omega)M(j\omega)e^{-j\omega L}$ are shown. These two vectors multiplied yield the perturbed Nyquist plot $K_{\mathrm{per}}(j\omega)$ (13).

On the strength of the above said, the following inequalities hold for the magnitude and phase of the perturbed open-loop system:

$$|K_{\mathrm{nom}}(j\omega)|\,(1 - \Delta) \le |K_{\mathrm{per}}(j\omega)| \le |K_{\mathrm{nom}}(j\omega)|\,(1 + \Delta). \tag{17}$$

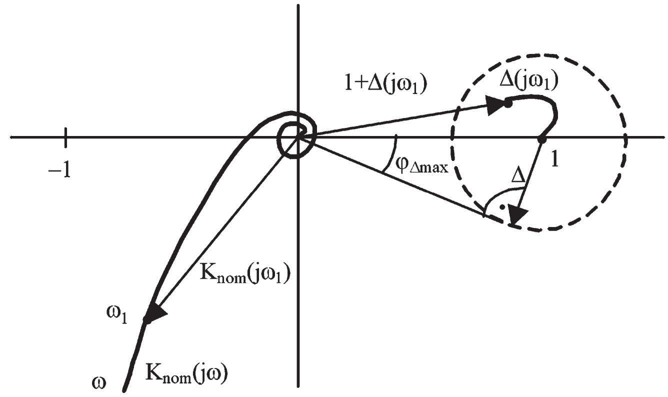

Fig. 2. Nyquist plots for the nominal system and perturbation.

Because the time delay L influences only the phase of the Nyquist plot while its magnitude $M(j\omega)$ is independent of L, the only frequency ω_0 such that

$$|K_{\mathrm{nom}}(j\omega_0)| \le \frac{1}{1 + \Delta} \tag{18}$$

$$\varphi(\omega_0) = -\pi + A_\Delta \tag{19}$$

can be determined analytically in simple cases or approximately in general.

For the ω_0 value obtained, the MFC controller parameters that provide a robustly stable (in Nyquist sense) perturbed closed-loop system are to be found from (18) in the following way:

1) the auxiliary controller R is tuned to the model (1) of the process (2) for a small phase margin (16), e.g., $A_\Delta = \pi/6$;
2) the model controller R_m is tuned to the process model (1) under the assumption that the phase margin (16) corresponds to the adopted magnitude of the maximal process perturbation (15), e.g., $\Delta = 0.85$.

The presented design method has been employed in [24] for unperturbed processes described by the nth order multi-time-lag model with the time constants spread between $T_{\min}$ and $T_{\max}$ [20]. Using the same design procedure for perturbed processes and the PID controller given by the transfer function

$$R_m(s) = \frac{k_c(1 + sT_i)(1 + sT_d)}{sT_i} \tag{20}$$

the allowable controller gain can be obtained as

$$k_c \le \frac{\omega_0 T_i\sqrt{\left(1 + \omega_0^2\overline{T}^2\right)^n}}{(1 + \Delta)k_m\sqrt{(1 + \omega_0^2T_d^2)\,(1 + \omega_0^2T_i^2)}} \tag{21}$$

where k_m is the gain of the nominal model and $\overline{T}$ is the process mean time constant defined by

$$\overline{T} = \frac{n}{\sum\limits_{i=1}^{n}\frac{1}{T_i}}, \qquad T_{\min} \le \overline{T} \le T_{\max}. \tag{22}$$

TABLE I
RULE BASE FOR THE FUZZY PD CONTROLLER

E \ ΔE	NL	NM	NS	ZR	PS	PM	PL
NL	ZR	ZR	ZR	ZR	ZR	ZR	ZR
NM	NL	NM	NM	NS	ZR	ZR	PS
NS	NL	NM	NM	NS	ZR	ZR	ZR
ZR	NM	NS	NS	ZR	PS	PS	PM
PS	ZR	ZR	ZR	PS	PM	PM	PL
PM	NS	ZR	ZR	PS	PM	PM	PL
PL	ZR	ZR	ZR	ZR	ZR	ZR	ZR

The ω_0 value in (21) is obtained from (19) by solving a fourth-order algebraic equation

$$\omega_0^4 \frac{2}{\pi} T_i T_d \overline{T} L + \omega_0^3 \left[\frac{2L}{\pi}(T_d\overline{T} + T_i\overline{T} + T_d T_i) + T_d T_i \overline{T} \frac{2A_\Delta}{\pi} + (n-3) T_d T_i \overline{T} \right] + \omega_0^2 \left[\frac{2L}{\pi}(T_d + T_i + \overline{T}) + \frac{2A_\Delta}{\pi}(T_d\overline{T} + T_i\overline{T} + T_d T_i) + (n-2)(T_d\overline{T} + T_i\overline{T}) - 3T_d T_i \right] + \omega_0 \left[\frac{2L}{\pi} + \frac{2A_\Delta}{\pi}(T_d + T_i + \overline{T}) + (n-1)\overline{T} - 2(T_d + T_i) \right] - \left(1 - \frac{2A_\Delta}{\pi}\right) \approx 0. \qquad (23)$$

IV. FUZZY MFC SYSTEM

Over the past few years, methods of artificial intelligence in general and fuzzy logic in particular are strongly applicable in industrial controllers. Controllers (fuzzy inference systems) based on fuzzy logic give a simple way to take account of experience gathered during the system operation. As shown in [11], [28], and [29], fuzzy realization of mechanisms known from the classic PID control theory presents no difficulties at all.

As suggested by results of numerous experiments, fuzzy-logic-based algorithms may be particularly adequate for processes that are difficult to control by linear time-invariant methods (Table I).

In such a case, nonlinear fuzzy PID algorithms are most often in use. However, the main difficulty encountered when employing them is intimate knowledge of the process to be controlled and of the fuzzy control itself, which has to be possessed by the user. This is because the design of nonlinear fuzzy PID controllers necessitates choosing many coefficients, the values of which cannot be determined analytically. This is also the case when increased robustness to varying process parameters is required [30]–[32]. The robust fuzzy MFC system presented below reduces the limitation mentioned. In fuzzy MFC, it is assumed that the structure of its controllers is always the same, and any known method for PID tuning should be applicable here with specific requirements to be met by MFC, as discussed above, taken into account.

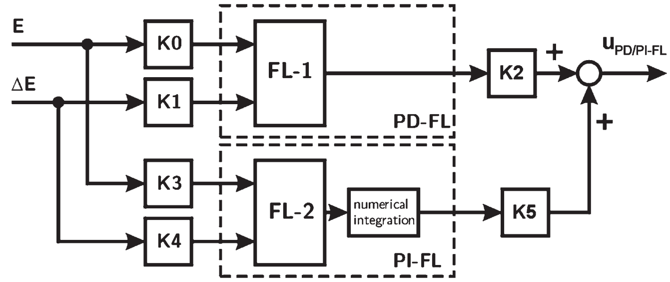

Fig. 3. Structure of PID-type fuzzy-logic PD-PI controller.

TABLE II
RULE BASE FOR THE FUZZY PI CONTROLLER

E \ ΔE	NL	NM	NS	ZR	PS	PM	PL
NL	ZR	ZR	ZR	ZR	ZR	ZR	ZR
NM	NL	NM	NM	NS	ZR	ZR	PS
NS	NL	NM	NM	NS	ZR	ZR	ZR
ZR	NM	NS	NS	ZR	PS	PS	PM
PS	ZR	ZR	ZR	PS	PM	PM	PL
PM	NS	ZR	ZR	PS	PM	PM	PL
PL	ZR	ZR	ZR	ZR	ZR	ZR	ZR

The proposed fuzzy MFC system employs two fuzzy PID controllers of a typical PD + PI parallel structure shown in Fig. 3.

Both PID controllers have been designed in such a way as to minimize the overshoot that may occur during the transients:

1) for small errors ($|\mathrm{E}| \approx 0$) and slowly varying errors ($|\Delta\mathrm{E}| \approx 0$), the controllers operate as a linear PID;
2) for very big absolute values of the error, the integration is stopped (the controllers operate as PD with saturation);
3) for quickly diminishing big and medium absolute values of the error, the negative gain of the path I is evaluated (to allow a lead-in time for the integral component of the controller output to be adjusted to the steady state).

To facilitate the process of tuning, it has been assumed that structures of the controllers and rule base surfaces of them are always the same. Another assumption adopted here is that tuning will be confined to the evaluation of respective scaling coefficients k_j shown also in Fig. 3. The coefficients are associated with the PID parameters through the fixed relationships

$$k_0 = k_c \quad k_1 = 0.5 k_c T_d \quad k_2 = 3.3$$
$$k_3 = \frac{50 k_c}{T_i} \quad k_4 = 0.5 k_c \quad k_5 = 0.033 \qquad (24)$$

where k_c, T_i, and T_d are settings of the respective linear controller within the MFC structure (R_m or R).

Rule bases for fuzzy controllers with their linear operation area marked are displayed in Table II. The corresponding surfaces are depicted in Figs. 4 and 5, where the linear operation area is also shown.

Figs. 6 and 7 illustrate the adopted fixed respective membership functions.

V. SOME EXPERIMENTAL RESULTS

The proposed MFC systems have been widely tested by both simulation and practical examinations. In simulation experiments, robustness and control quality for the perturbed

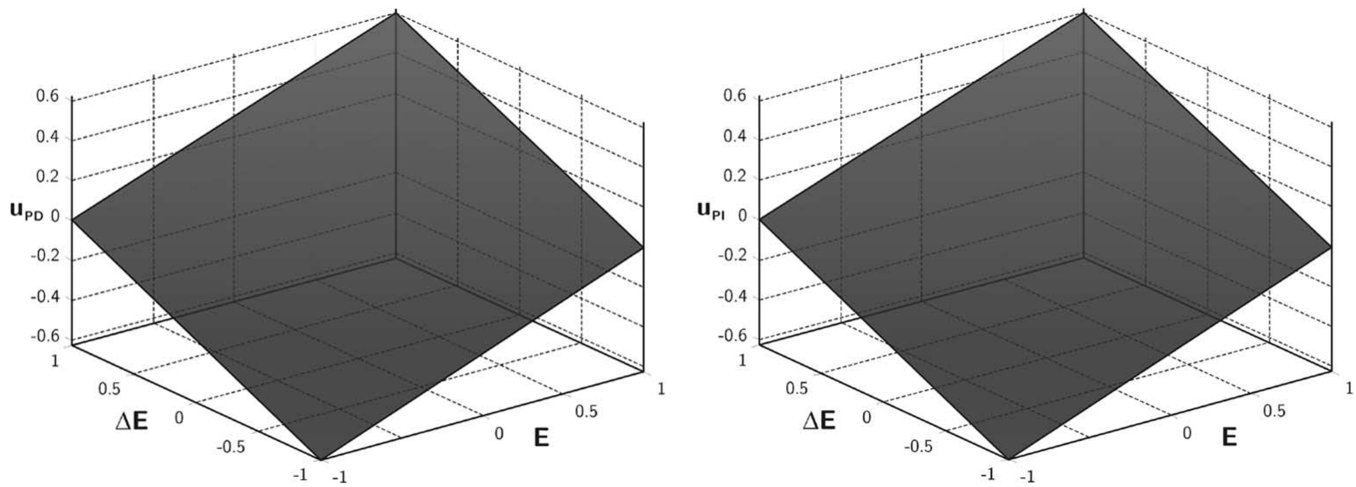

Fig. 4. Surface of the rule base for linear PD and PI actions.

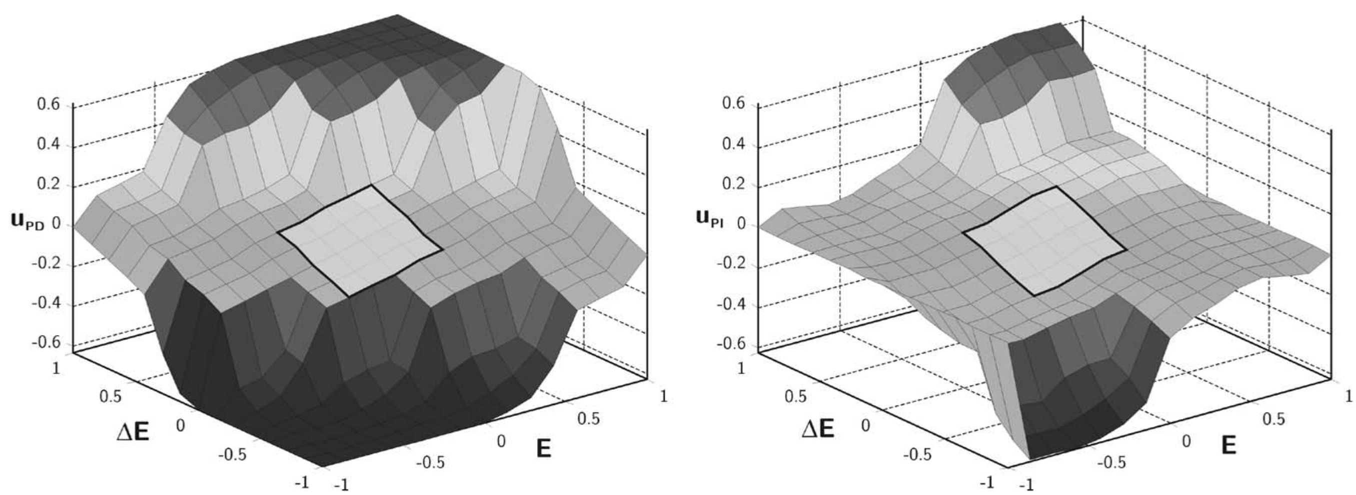

Fig. 5. Surface of the rule base for the proposed PD and PI actions.

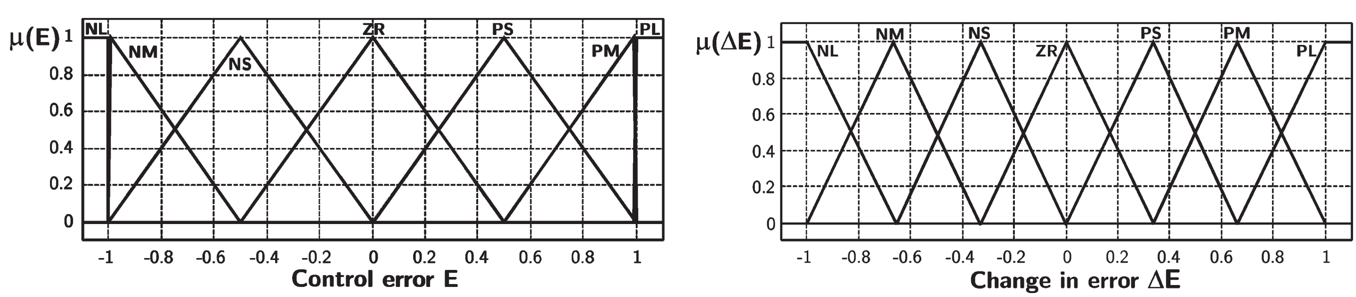

Fig. 6. Membership functions for input signals (error and error derivative).

plant gain and time constant, assuming constant parameters of both controllers, have been tested and compared with the classic control system. Both set point and plant load have been varied. First, tests have been conducted on the computer-simulated control structure under study. Second, tests on a computer-emulated programmable logic controller dedicated to the control of electrothermal processes with the MFC structure have been done. Third, practical tests have been carried out by implementing the proposed structures in a commercial PLC (previously emulated) and then the controller effectiveness for an electrothermal plant has been examined. As an illustration, selected test results are presented below.

A. Simulation Tests

For simulation purposes, the plant transfer had the form of a third-order time-lag system with time constants equal to 10 s, 20 s, and T_{3p} s, and the model was assumed with the same structure. Model time constant values were equal to 10, 20, and 40 s.

In all control schemes, the PID controllers had the transfer function (20). Both controllers have been tuned according to the rules proposed in Section III. The respective parameters are $k_c = 1.1$, $T_i = 40$ s, and $T_d = 10$ s for R_m, and $k_c = 2.0$, $T_i = 80$ s, and $T_d = 20$ s for R.

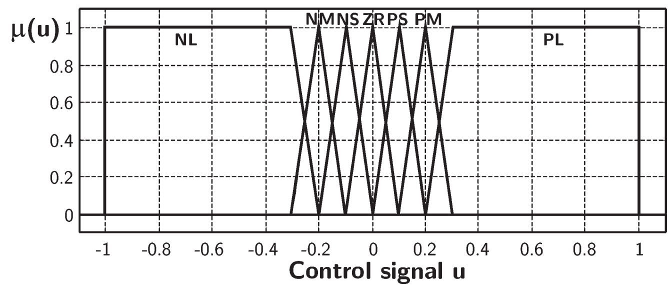

Fig. 7. Membership functions for u_{PD} and u_{PI} signals.

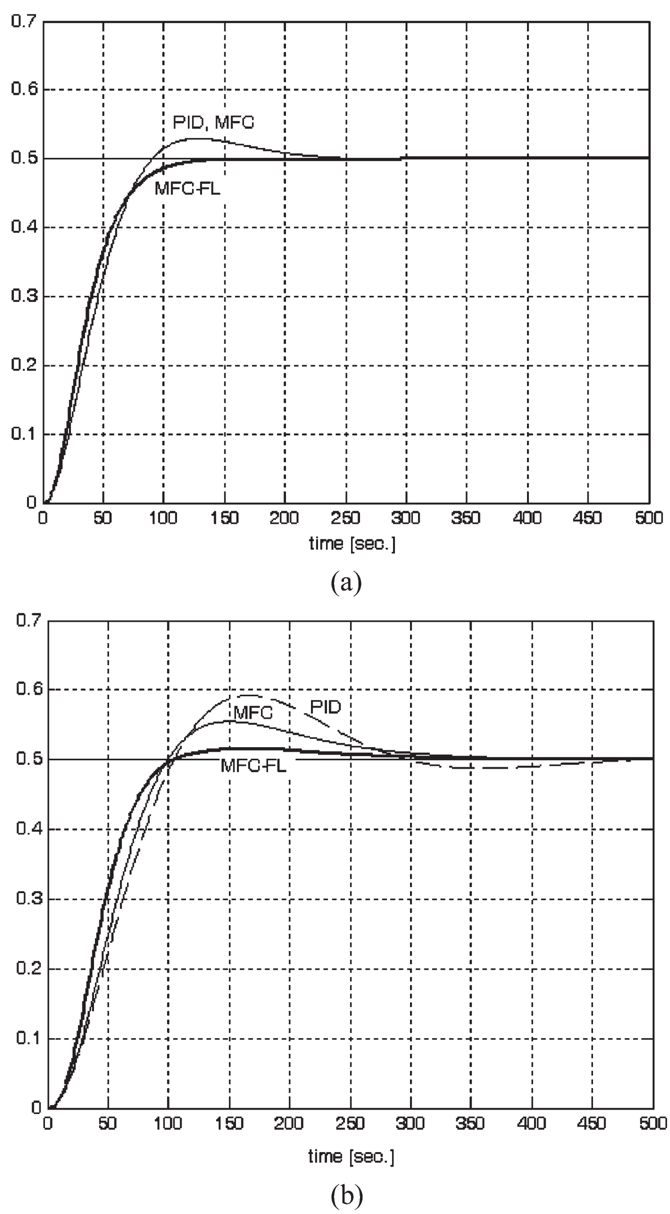

Fig. 8. Temperature responses obtained for the classic (a) MFC and (b) MFC-FL systems in case of nominal and perturbed processes.

Fig. 8 shows the plant outputs for the classic, MFC, and MFC-FL systems for two different values of the largest plant time constant ($T_{3p} = 40$ s and $T_{3p} = 80$ s, respectively).

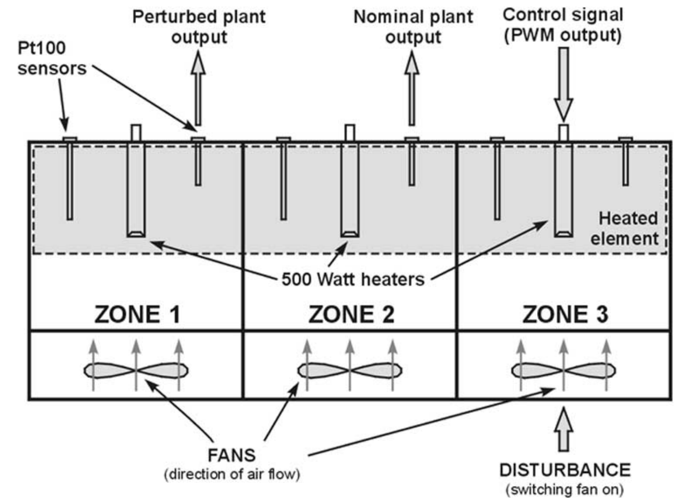

Fig. 9. Control plant used in tests.

B. Practical Tests

The proposed MFC system has been tested for effectiveness on temperature control of a multizonal laboratory electroheated plant (metal block with overall dimensions 50 cm × 10 cm × 5 cm equipped with a set of heaters of 500-W heat development and Pt100 sensors) depicted in Fig. 9.

Heaters were energized by a pulsewidth-modulated signal of a period of 4.095 s.

The static and dynamic properties of the employed process plant were strongly dependent on working points (heating power ratings). For the purposes of tuning, the adopted process model $M(s)$, which corresponds to energizing the third zone heater as an input, and temperature taken in the second zone as an output (P_{3-2}), is described by the transfer function $M(s) = 1/1((1+s340)(1+s1000))$.

Plant perturbation consisted of displacing the gauge point from the second zone into the first one (P_{3-1}).

During the control process, a strong disturbance was applied at $t = 7500$ s by switching on the fan of the third zone.

The model controller R_m and the corrective one R have been realized in an antiwindup version with their linear parts designed following the rules given in Section III, which yielded the transfer functions

$$R_m(s) = \frac{1.5(1+s170)(1+s1400)}{(s1400)}$$

$$R(s) = \frac{25(1+s340)(1+s2800)}{(s2800)}.$$

Fig. 10 illustrates the process of start-up and compensating the disturbance for the nominal plant (P_{3-2}) and classic and MFC control structures. Fig. 11 depicts the same processes for the perturbed plant (P_{3-1}).

VI. Conclusion

Results obtained from tests carried out on both the real process plant using an actual PLC with the implemented MFC structure, and employing simulation, lend support to the

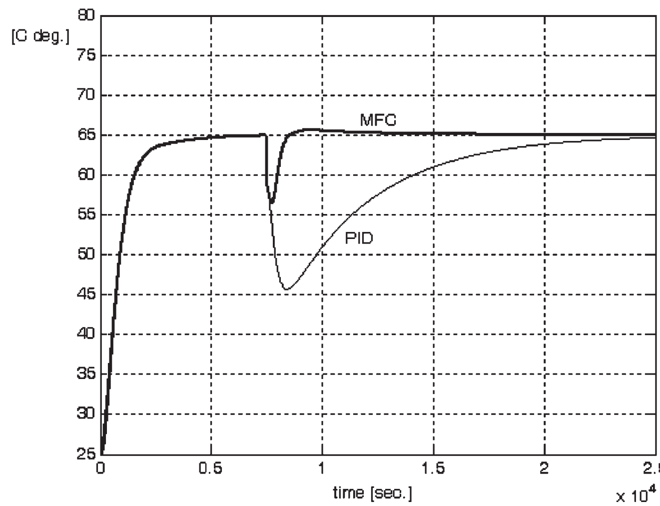

Fig. 10. Temperature response for the nominal process.

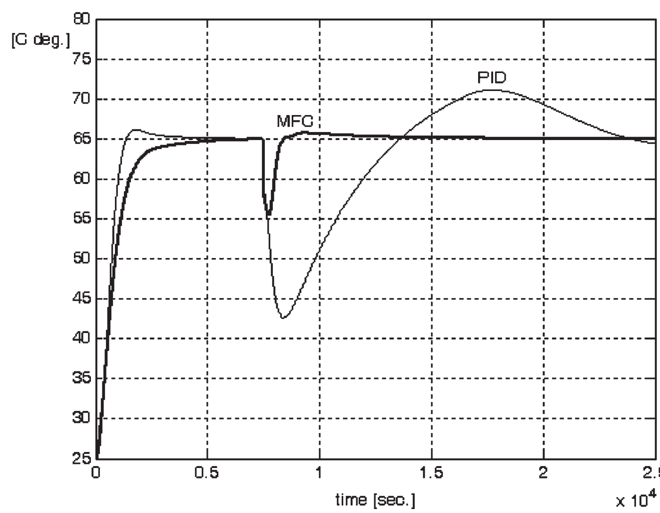

Fig. 11. Temperature response for the perturbed process.

validity of theoretical considerations. The proposed control structure exhibits a substantial robustness to plant parameter changes and a low susceptibility to inaccuracy of the model adopted to tune the controller. At the same time, the proposed structure is easy to implement on PLCs available on the market because it utilizes PID or fuzzy PID modules offered as part of standard software. Therefore, the proposed structure presents an effective alternative to control algorithms employed so far. The structure presented in the paper provides pretty high robustness to process parameter variations with respect to those of the nominal model used to tune the controller, and ensures control performance typical of PID well tuned to a stationary process.

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