EXPERIMENTAL EVALUATION OF A PLUG&CONTROL STRATEGY FOR LEVEL CONTROL

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Abstract: In this paper the application of a Plug&Control strategy (i.e. to automatically make the controller work properly after simply connecting it in the control architecture, without further intervention from the operator) to a typical level control problem is discussed. Experimental results are presented and discussed in order to verify the applicability of the strategy in an industrial context. It is concluded that the proposed strategy can be implemented successfully for the given problem, despite the presence of a nonlinear dynamics.

Keywords: Process control, PID controllers, self-tuning control, process parameter estimation, level control, time-optimal control.

1. INTRODUCTION

It is well-known that in the industrial context it is essential to obtain satisfactory control performances at the low possible cost. For this reason, industrial regulators are basically equipped with simple relays and Proportional-Integral-Derivative (PID) controllers, which are capable in general to guarantee a good cost/benefit ratio. In the last sixty years a lot of effort has been provided by researchers in the investigation of tuning rules for PID controllers (see (O'Dwyer, 2003) for an excellent collection of them) so that operators can exploit suitable design tools to achieve satisfactory performances for different kind of processes. Further, automatic tuning functionalities are given in almost all the industrial controllers on the market in order to facilitate the operator in setting up the controller (see e.g. (Aström *et al.*, 1993)). However, they might be time-consuming, especially if applied to processes with large time constants. Furthermore, during the identification phase, the experiments performed might not be compatible with the required operations of the process and therefore waste of materials, energy and so on occurs.

Actually, in many cases (for example in inventory control) extremely tight performances are not required and shortening the time of the start-up phase of the plant and of the tuning of the controller is of major concern.

In this context, a Plug&Control strategy (i.e. to automatically make the controller work properly after simply connecting it in the control architecture, without further intervention from the operator) is highly desirable. At least to the author knowledge, the first Plug&Control strategy has been proposed in (Pfeiffer, 1999; Pfeiffer, 2000) for temperature control. Then, in (Visioli, 2003) a time-optimal Plug&Control strategy has been developed for integrating and first-order plus dead-time (FOPDT) processes. It relies first on the use of a three-state (open-loop) controller to achieve a minimum time output transition. During the first part of the transient response a least squares algorithm (Sung *et al.*, 1998) is adopted in order to estimate the process model. Then, a PI(D) controller, tuned according to the estimated model, is applied.

In this paper, experimental results related on the devised technique are presented and analysed, aiming at verifying the real applicability of the method in industrial settings. In particular, a level control problem is addressed by means of a laboratory scale experimental setup. Level control applications are commonly found in many industrial plants and open-loop and PI controllers are usually adopted (Pan *et al.*, 2005). The choice of the design parameters is discussed and the use of a recursive least squares algorithm is proposed to improve the method.

The paper is organised as follows. In Section 2 the addressed Plug&Control strategy is briefly reviewed. The experimental setup adopted for its application is described in Section 3. Experimental results are presented and discussed in Section 4 and finally conclusions are drawn in Section 5.

2. THE TIME-OPTIMAL PLUG&CONTROL STRATEGY

The proposed Plug&Control strategy (Visioli, 2003) is based on the combined use of three-state and PID control in order to perform a transition from one setpoint value to another, as required by the process operation. No a priori knowledge of the process model parameters is required. The identification phase is performed by means of a simple least squares based methodology (Sung *et al.*, 1998) in the first part of the transient response. The nice feature of the method presented is that the three-state control can be exploited to provide in principle, for FOPDT processes, a time-optimal transition subject to the saturation limits of the actuator.

Assume that the process dynamics can be described by the following (unknown) FOPDT transfer function:

$$P(s) = \frac{K}{Ts+1}e^{-Ls} := \tilde{P}(s)e^{-Ls} \quad K > 0,\ T > 0 \quad (1)$$

and denote u as the controller output and y as the process output. Suppose now that an output transition from y_0 to $y_0 + y_1$ is then required to be performed, starting from time t_0 (assume that the process is at an equilibrium point with $u_0 := u(t_0)$ and $y_0 := y(t_0)$). Then, the following time-optimal Plug&Control (TOPC) algorithm (Visioli, 2003) can be applied.

TOPC algorithm

(1) Set u_{max} and u_{min} as the maximum and minimum values respectively of the control variable u during the three-state control and calculate $u^+ = u_{max} - u_0$ and $u^- = u_{min} - u_0$.
(2) Set flag=1.
(3) At time $t = t_0$ set $u = u_{max}$.
(4) When $y > y_0 + NB$ set $t_1 = t$ and $\hat{L} = t_1 - t_0$ (estimated dead time of the process).
(5) At time $t = t_1$ start the collection of data for the identification of the process model.
(6) When $y > y_0 + \bar{y}$:
  (a) Set $t_2 = t$.
  (b) Apply the identification procedure described in (Sung *et al.*, 1998), thus obtaining $\hat{K}$ (estimate of K) and $\hat{T}$ (estimate of T).
  (c) Apply a PI(D) tuning rule based on the model identified.
  (d) Calculate

$$t_{s1} = t_0 - \hat{T}\ln\left(\frac{u^+ - \frac{y_1}{\hat{K}}}{u^+}\right). \quad (2)$$

  (e) If $t_{s1} < t_2$ then set $t_{s1} = t_2$, flag=0 and calculate

$$t_{s2} = t_{s1} - \hat{T}\ln\left(\frac{\frac{y_1}{\hat{K}} - (u^-)}{-u^+\exp\left(-\frac{t_{s1}}{\hat{T}}\right) + u^+ - u^-}\right). \quad (3)$$

(7) If flag=1 then set $u = u_{max}$ when $t \le t_{s1}$ and $u = u_0 + y_1/\hat{K}$ when $t > t_{s1}$, else set $u = u_{min}$ when $t \le t_{s2}$ and $u = u_0 + y_1/\hat{K}$ when $t > t_{s2}$.
(8) When $t > \hat{L} + t_{s1}$ (if flag=1) or when $t > \hat{L} + t_{s2}$ (if flag=0) apply the PI(D) controller.

Remark 1. It has to be noted that a bumpless transfer (Aström and Hägglund, 1995) has to be applied at step 8 at the time of switching from the three-state to the PID controller.

From a practical point of view different technical problems have to be solved. In particular the choice of u_{max}, u_{min} (whose value in practical cases could be conveniently selected less than the maximum allowed by the actuator), NB (the noise band (Shinskey, 1994; Aström *et al.*, 1993)) and $\bar{y}$ (the value of the output that determines when to stop to collect the data in order to apply the least square estimation procedure) has to be addressed.

The main aim of this paper is to verify that these problems can be solved in a practical context, yielding therefore to a methodology that can be implemented in Distributed Control Systems as well as in single station controllers.

3. EXPERIMENTAL SETUP

A laboratory experimental setup (made by KentRidge Instruments) has been employed (see Figure 1). Specifically, the apparatus consists of a small perspex tower-type tank (whose area, which is supposed to be unknown, is $A = 40$ cm^2) in which a level control is implemented by means of a PC-based controller whose sampling time is 1 ms. The tank is filled with water by means of a pump whose speed is set by a DC voltage (the manipulated variable), in the range 0-5 V, through a PWM circuit. The tank is fitted with an outlet at the base in order for the water to return to a reservoir. The measure of the level h of the water is given by a capacitive-type probe that provides an output signal between 0 (empty tank) and 5 V (full tank). For the sake of simplicity, in the following the level variable will be expressed in Volts.

The process can be modelled by the following differential equation:

$$A\frac{dh}{dt} = Q_i - Q_o \quad (4)$$

where Q_i and Q_o are the input and output flow rate respectively. Note that the system is actually nonlinear, since the output flow rate depends on the square root of the level, i.e.

$$Q_o = a\sqrt{2gh}$$

where a is the cross sectional area of the outflow orifice and g is the gravitational constant.

Fig. 1. The experimental setup (only one tank has been adopted in the experiments).

Since the apparent dead time of the system is rather small with respect to its dominant time constant, the case where an additional dead time of 8 s has been added via software to the process input has been also considered. The values of the parameters of the model are unknown. However, the knowledge of the type of process will be exploited in the next in order to select appropriately the design parameters of the TOPC algorithm.

4. EXPERIMENTAL RESULTS

4.1 Choice of the experiment

In order to apply successfully the Plug&Control strategy described in Section 2 in the presence of noise, it has to be taken into account that, obviously, a significant (part of a) transient response has to be provided to the least squares algorithm in order to obtain a sufficiently accurate estimation of the parameter (for the purpose of the time-optimal control and of the tuning of the PID controller). This is consistent with the scope of the strategy, as it is expected that the tank has to be filled at a rather high level at the start-up of the plant (thus, a too low value of y_1 cannot be selected). In this context, the selection of the value of u_{max} is a crucial issue (whilst u_{min} can be trivially fixed to zero). Actually, if the gain of the process is high, fixing u_{max} at the highest value allowed by the actuator might yield to the saturation of the process output in a too short time for a successful application of the least squares method (in the presence of noise). Similarly, the selection of a too low value of u_{max} might prevent the attainment of the value $y_0 + y_1$ for the process output.

It appears that the knowledge of the kind of process is very useful in easily handle these technical problems. By considering the tank apparatus described by the model (4), it is straightforward to deduce that the gain of the process tends to increase as the level increases. Thus, the following experiment, which is sound from an industrial point of view, has been first performed in order to evaluate the TOPC algorithm. Starting from the tank empty, first a manual (open-loop) control is adopted to partially fill the tank. In particular, the controller output is set at $u_0 = 1.9$ V and the end of the transient response (i.e. when the process output attains its steady-state value y_0) is awaited. When the equilibrium point is attained, the noise band NB is estimated. Then, by taking into account the previous considerations and the measured value of y_0, it is fixed $u_{max} = 3.4$ V (i.e. $u^+ = 1.5$, whilst being $u_{min} = 0$ it is $u^- = -1.9$) and $y_1 = 3$ V (note that the more the value of y_1 is high, the more the effects of the nonlinearity is evident). The value of $\bar{y}$ is then fixed at 2 V (i.e. at two thirds of the amplitude of the set-point step). This choice is in accordance with the simulations shown in (Visioli, 2003), however it will be better discussed in the next. When the process output attains the value $y_0+\bar{y}$, the values of t_{s1} (and possibly t_{s2}) are calculated and a PI controller (the derivative action has not been adopted) whose transfer function is expressed as

$$C(s) = K_p\left(1+\frac{1}{T_i s}\right) \qquad (5)$$

is tuned by following an Internal Model Control approach, according to the following formula (Rivera *et al.*, 1986)

$$K_p = \frac{T}{\lambda K} \quad T_i = T \qquad (6)$$

where

$$\lambda = \max\{2.3L, 0.15T\}. \qquad (7)$$

Note that, with respect to the original formula, the value of K_p has been conveniently lowered in order to take into account the nonlinear dynamics. Finally, in order to verify the effectiveness of the designed PI controller, two set-point changes (of -1 V each) have been required after the end of the TOPC strategy.

4.2 Basic TOPC algorithm

The result of an experiment on the system without the additional time delay is reported in Figure 2. At time $t_0 = 0$ it is ($u_0 = 1.9$ V and) $y_0 = 1.84$ V (note that this value has been calculated as the mean of the last 20 values of the process output) and the (previously) estimated noise band is 0.01 V. After having set $u = u_{max}$, the apparent dead time of the process is estimated as $\hat{L} = t_1 = 0.9$ s (see step (4) of the TOPC algorithm). Then, the process output attains the value $y_0 + \bar{y} = 3.84$ V at time $t_2 = 26.5$ s. By applying the least squares algorithm to the data collected in the time interval $[t_1, t_2]$ it results $\hat{K} = 2.5$ and $\hat{T} = 36.6$. Consequently, the PI controller parameters are selected as $K_p = 2.67$ and $T_i = 36.6$ and it is calculated $t_{s1} = 58.9$ s. Thus, at time $t = t_{s1}$ it is set $u = u_0 + y_1/\hat{K} = 3.1$ V for a time interval of $\hat{L} = 0.9$ s and then the control switches from the three-state controller to the PI controller. It can be noted

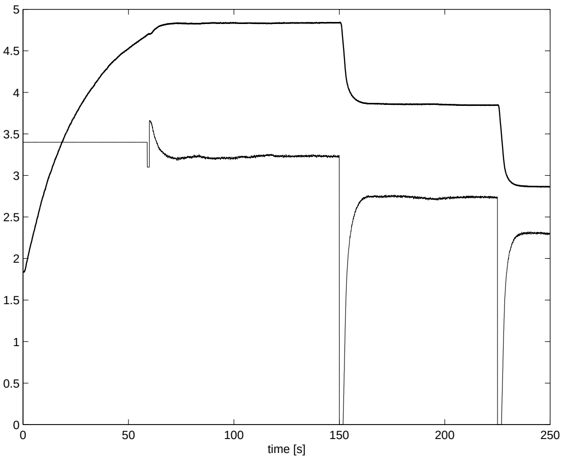

Fig. 2. Results of the basic algorithm on the system without additional delay ($y_1 = 3$ V, $\hat{L} = 0.9$ s, $t_2 = 26.5$ s, $t_{s1} = 58.9$ s); thick line: process output (V); thin line: controller output (V).

that, due to the unavoidable inaccuracies in the estimation of the parameters, the set-point value is not attained at time $t = \hat{L} + t_{s1} = 59.8$ s and PI controller immediately compensates the (small) residual system error of 0.14 V and yield the controller output to the correct steady-state value of 3.23 V. The response to the two set-point changes required at time $t = 150$ s and $t = 225$ s confirms that the PI controller is well-tuned.

The case where the additional dead time has been adopted is reported in Figure 3. In this case we have $y_0 = 1.8$ V, $\hat{L} = 8.6$ s, $t_2 = 37.2$ s, $\hat{K} = 2.43$, $\hat{T} = 36.8$, $K_p = 0.77$, $T_i = 36.8$ and $t_{s1} = 63.7$ s. It can be noted that, as expected since the three state controller is in open-loop and the time delay is excluded from the computation of the switching times, the presence of a time delay does not represent a problem for the TOPC algorithm.

From the presented results it appears that the devised methodology gives satisfactory results provided that the values of the design parameters are suitably chosen. Indeed, as already mentioned, it is obvious that a too low value of the set-point change cannot be selected in conjunction with a high value of u_{max} (and viceversa). For example, if it is selected $y_1 = 1.5$ V with again $u_{max} = 3.4$ V and $u_{min} = 0$, the whole part of the transient of the process output from y_0 to $y_0 + y_1$ (i.e. for $\bar{y} < y_1$) is not sufficient for the least squares algorithm to provide a consistent result. This suggests to adopt a recursive least squares algorithm for the process parameter estimation, in order to automatically select the parameter $\bar{y}$ which is actually the crucial issue of the Plug&Control strategy.

4.3 *Use of a recursive least squares algorithm*

The TOPC algorithm can be modified simply as follows. Instead of collecting the data in the time interval $[t_1, t_2]$ and of applying the least squares algorithm proposed in (Sung *et al.*, 1998) at the end of interval, a

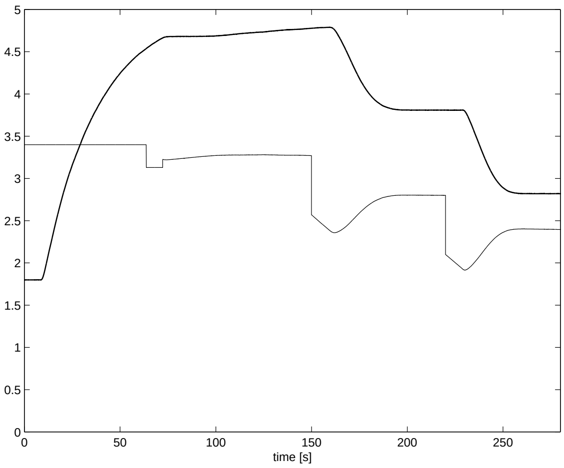

Fig. 3. Results of the basic algorithm on the system with additional delay ($y_1 = 3$ V, $\hat{L} = 8.6$ s, $t_2 = 37.2$ s, $t_{s1} = 63.7$ s); thick line: process output (V); thin line: controller output (V).

(standard) recursive least squares algorithm (Aström and Wittenmark, 1995, page 51) is employed, starting at time instant $t = t_1$, until the estimated parameters value converges. From a practical point of view, the algorithm can be stopped (at time $t = t_2$) when the difference between the estimated values of K and T at a given time instant and those at the previous one is less than $1 \cdot 10^{-4}$. Formally, the TOPC algorithm should be modified at steps (5) and (6) as follows (denote T_c as the sampling time):

Modified TOPC algorithm

$\vdots$

(5) At time $t = t_1$ start the recursive least squares algorithm (Aström and Wittenmark, 1995, page 51).
(6) When $|\hat{K}(t) - \hat{K}(t - T_c)| < 1 \cdot 10^{-4}$ and $|\hat{T}(t) - \hat{T}(t - T_c)| < 1 \cdot 10^{-4}$:
    (a) Set $t_2 = t$.
    (b) Set $\hat{K} = \hat{K}(t_2)$ and $\hat{T} = \hat{T}(t_2)$

$\vdots$

Hence, with this modified algorithm there is no more need of parameter $\bar{y}$. The process output and the controller output related to the case without and with the additional delay and with $y_1 = 3$ V are reported in Figures 4 and 5 respectively. It results $y_0 = 1.8$ V, $\hat{L} = 1.1$ s, $t_2 = 28.0$ s, $\hat{K} = 2.24$, $\hat{T} = 34.0$, $K_p = 2.97$, $T_i = 34.0$ and $t_{s1} = 75.7$ s for the delay free case and $y_0 = 1.75$ V, $\hat{L} = 8.8$ s, $t_2 = 36.5$ s, $\hat{K} = 2.21$, $\hat{T} = 34.0$, $K_p = 0.76$, $T_i = 34.0$ and $t_{s1} = 79.0$ s for the case with the added delay. It is evident that in this case results are very similar to those obtained with the basic algorithm.

To appreciate the improvement due to the use of the modified algorithm, the case where $y_1 = 1.5$ V, that cannot be handled by the basic algorithm, is considered. Results for the delay free case are reported in Figure 6. It can be noticed that, after the determina-

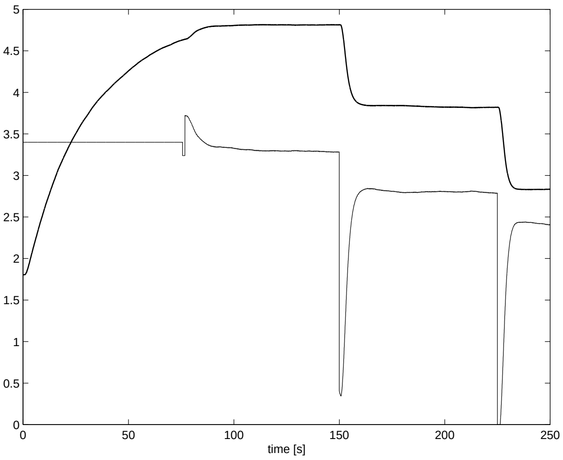

Fig. 4. Results of the modified algorithm on the system without additional delay ($y_1 = 3$ V, $\hat{L} = 1.1$ s, $t_2 = 28.0$ s, $t_{s1} = 75.7$ s); thick line: process output (V); thin line: controller output (V).

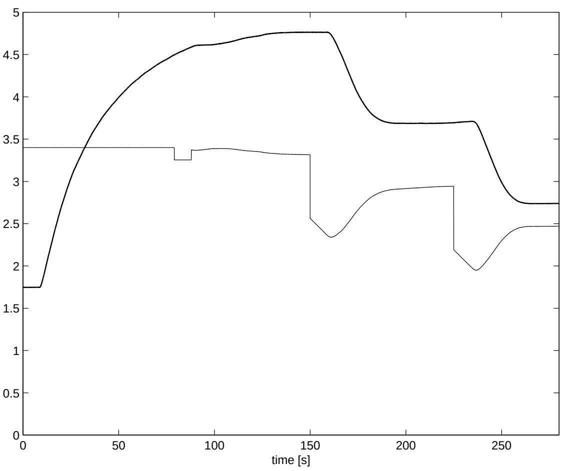

Fig. 5. Results of the modified algorithm on the system with additional delay ($y_1 = 3$ V, $\hat{L} = 8.8$ s, $t_2 = 36.5$ s, $t_{s1} = 79.0$ s); thick line: process output (V); thin line: controller output (V).

tion of $y_0 = 1.72$ V and $\hat{L} = 0.9$ s, the convergence of the parameters estimation ($\hat{K} = 2.23$, $\hat{T} = 35.4$) is established at time $t = t_2 = 30.8$ s. As t_{s1} results to be equal to 21.1 s, it is set $t_{s1} = t_2$ and it is calculated $t_{s2} = 33.4$. Thus, in the time interval $[t_{s1}, t_{s2}]$ the controller output is set to $u_{min} = 0$ before being set to $u = u_0 + y_1/\hat{K} = 2.57$ V until the PI controller ($K_p = 2.99$, $T_i = 35.4$) is applied. It appears that the output response presents an (unavoidable) overshoot, but the ideal minimum-time output transition from y_0 to $y_0 + y_1$ is almost achieved due to the low estimation error.

Figure 7 reports the results of the application of the method to the system with the additional delay. In this case it results $y_0 = 1.70$ V, $\hat{L} = 9.0$ s, $t_2 = 37.5$ s, $\hat{K} = 2.23$, $\hat{T} = 34.6$, $t_{s2} = 41.5$ s, $K_p = 0.75$ and $T_i = 34.6$. The presence of a dead time makes the influence of the estimation inaccuracies more evident, but the overall performance is still satisfactory.

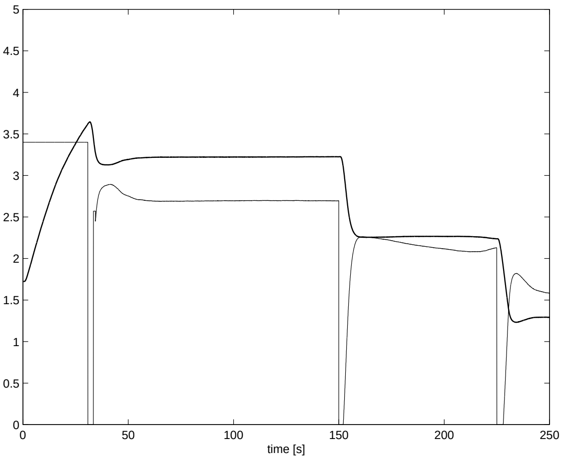

Fig. 6. Results of the modified algorithm on the system without additional delay ($y_1 = 1.5$ V, $\hat{L} = 0.9$ s, $t_2 = t_{s1} = 30.8$ s, $t_{s2} = 33.4$ s); thick line: process output (V); thin line: controller output (V).

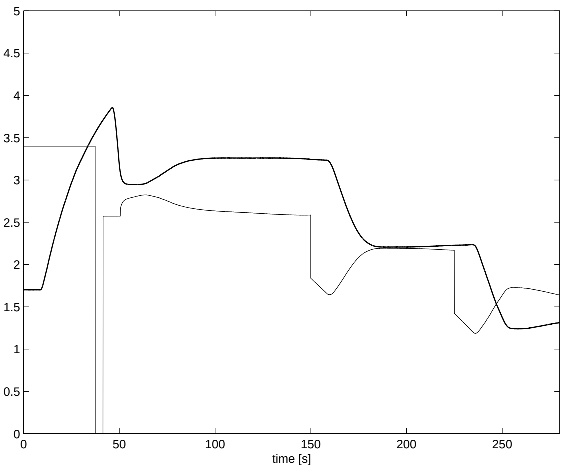

Fig. 7. Results of the modified algorithm on the system with additional delay ($y_1 = 1.5$ V, $\hat{L} = 9.0$ s, $t_2 = t_{s1} = 37.5$ s, $t_{s2} = 41.5$ s); thick line: process output (V); thin line: controller output (V).

4.4 Discussion

The results presented in the previous subsection show that the Plug&Control strategy can be effectively adopted in the context of level control. Actually, it appears that, as expected, if the amplitude of the initial set-point step y_1 is high, then a monotonic response is attained, while if it is low an overshoot might occur. However, in this latter case, the presence of an overshoot is not of main concern, as h remains far from its allowed maximum value.

The choice of u_0 and y_1 in the previous examples has been motivated by the need of covering a large portion of the working zone of the plant in order to verify the effects of its nonlinearity. To verify that the choice of the design parameters is indeed not critical, consider the case where $u_0 = 1.5$ V and $u_{max} = 4$ V (u_{min} is set again to 0 V). In case of no additional delay, results for $y_1 = 3$ V are reported in Figure 8 (it is $y_0 = 1.16$ V, $\hat{L} = 0.6$ s, $t_2 = 20.0$ s, $t_{s1} = 24.6$ s, $K = 1.95$, $T = 25.5$, $K_p = 3.42$ and $T_i = 25.5$), and for

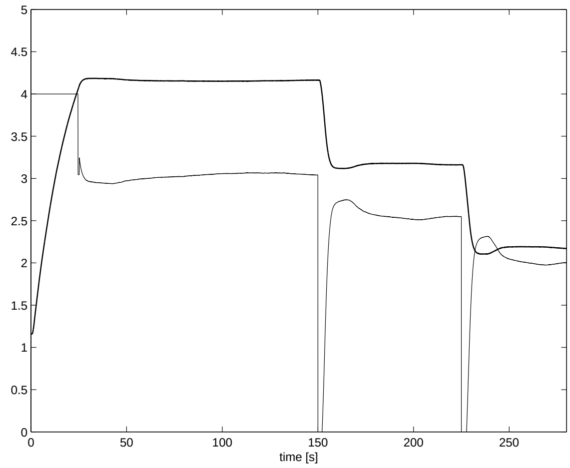

Fig. 8. Other results of the modified algorithm ($y_1 = 3$ V, $\hat{L} = 0.6$ s, $t_2 = 20.0$ s, $t_{s1} = 24.6$ s); thick line: process output (V); thin line: controller output (V).

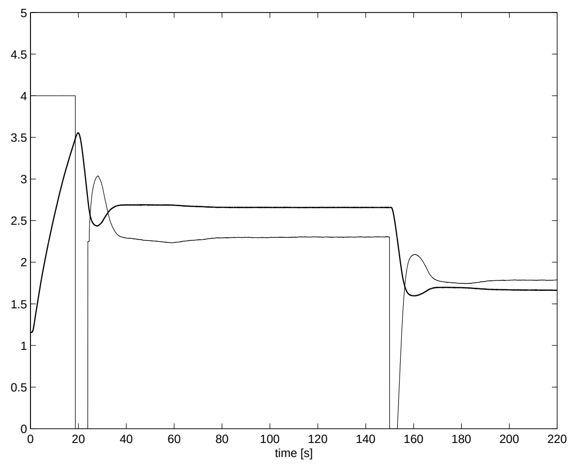

Fig. 9. Other results of the modified algorithm ($y_1 = 1.5$ V, $\hat{L} = 0.6$ s, $t_2 = t_{s1} = 18.5$ s, $t_{s2} = 23.9$ s); thick line: process output (V); thin line: controller output (V).

$y_1 = 1.5$ V are shown in Figure 9 (it is $y_0 = 1.16$ V, $\hat{L} = 0.6$ s, $t_2 = 18.5$ s, $t_{s2} = 23.9$ s, $K = 2.0$, $T = 28.7$, $K_p = 3.33$ and $T_i = 28.7$). Finally, the case where $u_{max} = 3$ V and $y_1 = 1.5$ V is presented in Figure 10 (it is $y_0 = 1.14$ V, $\hat{L} = 0.6$ s, $t_2 = 15.0$ s, $t_{s1} = 18.4$ s, $K = 1.8$, $T = 23.0$, $K_p = 3.70$ and $T_i = 23.0$). Note that in the last two examples, the second set-point step after the end of the modified TOPC algorithm has not been applied as a too low value of the set-point would have resulted.

It is apparent that similar results are obtained in the different cases, so that it can be concluded that the choice of the design parameters is not critical.

5. CONCLUSIONS

In this paper the use of a Plug&Control strategy in a level control application has been investigated. The original methodology presented in (Visioli, 2003) has been improved by adopting a standard recursive least

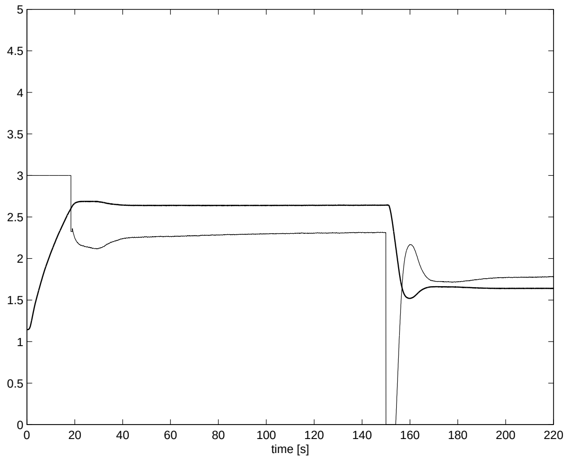

Fig. 10. Other results of the modified algorithm ($u_{max} = 3$ V, $y_1 = 1.5$ V, $\hat{L} = 0.6$ s, $t_2 = 15.0$ s, $t_{s1} = 18.4$ s); thick line: process output (V); thin line: controller output (V).

squares estimation of the process parameters. From the presented results, the effectiveness of the technique in practical cases appears.

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