Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal 2024, 18(1), 89–97
https://doi.org/10.12913/22998624/176832
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Received: 2023.11.08
Accepted: 2023.12.12
Published: 2024.01.15

Implementation of PID Autotuning Procedure Based on Doublet-Pulse Method in PLC Controller

Michał Awtoniuk[1*], Robert Sałat[2], Miłosz Worwa[2], Volodymyr Reshetiuk[1]

[1] Institute of Mechanical Engineering, Warsaw University of Life Sciences, ul. Nowoursynowska 166, 02-787 Warsaw, Poland

[2] Faculty of Electrical and Computer Engineering, Cracow University of Technology, ul. Warszawska 24, 31-155 Krakow, Poland

* Corresponding author's e-mail: michal_awtoniuk@sggw.edu.pl

ABSTRACT

We combined the Doublet-Pulse method with the Approximate M-constrained Integral Gain Optimisation tuning rules and implemented this combination as a stand-alone autotuning procedure in Siemens S7-1200 PLC controller. The procedure was tested for three types of simulated plant models. The simulated models were diverse in terms of dynamics, as we used lag-dominated, balanced, and delay-dominated models. We compared the doublet-pulse method with the classical identification method in the form of step response, i.e. method of moments. We conducted tests for three scenarios, i.e., a step change in the set point, set point trajectory tracking and load disturbances. To assess the control quality, we used integral index IAE. The described method is universal and can also be implemented in controllers from other manufacturers.

Keywords: doublet-pulse method, system identification, PID, PLC

INTRODUCTION

Auto tuning is considered as a method that allows the Proportional-Integral-Derivative (PID) controller parameters to be selected automatically without human intervention, and its only task is to call the auto tuning procedure. In general, most PID auto-tuning methods involve finding the dynamics of a model and matching it with models of generally low order, i.e., the first or the second order [1]. Automatic tuning of PID controllers is a useful feature for those who do not have time or knowledge to manually tune their control loops. Often in industry, a single plant may have hundreds or thousands of different control loops, e.g., temperatures, flows, levels, concentrations, etc., that need to be controlled [2,3]. The benefit of a fast and reliable way to find the proper controller parameters is very valuable in this case. One procedure that is widely used in industry and involves auto-tuning is the relay method proposed by Åström and Hägglund. The Åström and Hägglund [4] autotuner, which was developed in the 1980s, is still the most common in industrial control systems [5]. This method has been implemented in PLCs (programmable logic controllers) such as ABB, Siemens, Emerson etc. [6,7]. The principle of autotuning using the relay method is as follows [8,9]. In a closed feedback loop, a relay switches between two values depending on the process output, triggering its oscillation. From the oscillations, process data can be collected and used to tune the PID controller. The method operates in a closed loop around the operating point which allows for forcing small oscillations (sustained) and short experiment time, unlike the Ziegler-Nichols method which sometimes takes the system to the limit of stability [10,11]. The second type of auto-tuning procedures are methods based on the so-called single step test in open or closed loop control [12]. In general, the step test is performed when the process is in zero initial condition or in any steady state. The process response to a step change in the process input is observed to identify the model. It is evident that a larger step change size can facilitate better observation of the transient response. In practice, however, this is subject to limitations related to the complexity of the process. Most current step identification methods have been developed based on zero initial conditions or a non-zero steady state to perform a step test. Unlike an open-loop unit step, when a step test is performed in a closed-loop, the step change is usually added to the set point rather than to the process input. This is because any external signal added to the process input acts as a disturbance that can be rejected by the closed-loop feedback mechanism. In addition, the closed-loop step test is usually performed after the closed-loop system has already switched to a steady state.

The most recent trend in the application of autotuning are methods from the group of relay methods called biased (asymmetrical). They are different from classical relay methods by using forcing, which is asymmetric. The advantage of using asymmetric relay is that you can calculate the static gain from the equation for the ratio of the integrals of the output signal to the input signal, which is not possible in the classical method, since symmetry causes division by zero. A further advantage is also the easy calculation of the normalized time delay through the ratio of on-time to off-time [13]. Taken together, the general trend in setting selection procedures is to simplify the process to methods in which simple and short setting selection methods are used. According researches [4,14], it has been found that only one-third of the loops worked correctly, one-third had poorly selected settings, and the last third of the loops had controllers operating in a manual mode. This study explicitly show that where the selection process is complex or the identification experiment is long and complex, control engineers tend to leave such loops poorly or not tuned at all.

Briefly, the paper is structured as follows. Section 2 is focused on describing the concept of Doublet-Pulse method. Next, in Section 3 the authors highlight the data acquisition system setup, including description of testing scenarios. The summary of results is then provided in Section 4, and discussion are drawn in Section 5. Finally, conclusions and future studies are provided in Section 6. The novelty of the paper is the implementation of the theoretical system identification method in a real PLC and a comprehensive attempt to evaluate it. To the best of our knowledge, no paper has yet been published that utilises the doublet-pulse method as a component of PID controller tuning procedure in a PLC.

INTRODUCTION TO DOUBLET-PULSE METHOD

One variant of the step identification method is the doublet-pulse (DP) method. The experiment is performed at a steady state, for which the plant output is y_0 and the control signal is u_0. In the first stage, a step excitation with amplitude a is introduced. The controller then takes the value $u_{max} = u_0 + a$. Then, after an assumed time T_p, a second step excitation of the control signal is introduced, this time to the level of $u_{min} = u_0 - a$. The value of u_{min} is also maintained for time T_p, after which the control signal returns on its initial value, i.e. u_0. Figure 1 shows the example of the experiment in the DP method. The experiment is designed to determine the maximum y_{max} and minimum y_{min} values of the output signal y and the time of occurrence of the extreme, i.e. t_{max}. These are used to determine the parameters of the first order lag plus time delay (FOTD) model described by the transfer function $M(s)$. Calculations are performed according to the equations:

$$M(s) = \frac{Ke^{-sL}}{Ts+1} \tag{1}$$

$$K = -\frac{(y_{max} - y_0)^2}{a(y_{min} - y_0)} \tag{2}$$

$$T = \frac{T_p}{\log\left(1 + \frac{y_{max} - y_0}{y_0 - y_{min}}\right)} \tag{3}$$

$$L = t_{max} - T_p \tag{4}$$

where: K – static gain, T – time constant, L – delay time, a – amplitude of the step excitation, T_p – pulse time, y_{max} – the maximum value of the output signal y during the experiment, y_{min} – the minimum value of the output signal y during the experiment, t_{max} – time to reach y_{max}.

There are no mandatory values for the pulse time T_p, as well as the amplitude a. It is assumed that the time T_p should be longer than the object delay L. On the other hand, the value of the amplitude a should be selected in such a way that the response of the object is greater than the measurement noises [15].

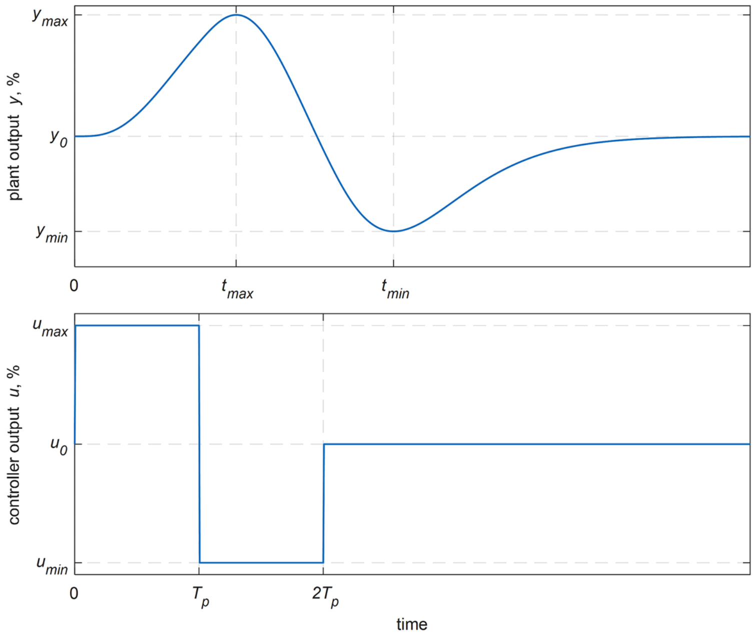

Figure 1. Graphical interpretation of parameters calculated in the doublet-pulse method

MATERIALS AND METHODS

The doublet-pulse identification algorithm was implemented in a Siemens PLC model S7 1214C DC/DC/DC with firmware version of 4.2. The program was written in ladder language in TIA Portal v15 software. The programme performs three basic functions:

- simulation of control objects,
- system identification and calculation of controller's parameters,
- execution of the PID algorithm.

In our study, we considered three simulated plants P_1, P_2 and P_3. We adopted the same plants as in the work [16] so that we could compare the results obtained with another method - the Method of Moments (MM). The plants were diverse in terms of dynamics: P_1 was lag-dominated, P_2 was balanced, while P_3 was delay-dominated. The plants are described by transfer functions:

$$P_1(s) = \frac{1}{(s+1)(0.1s+1)(0.01s+1)(0.001s+1)} \tag{5}$$

$$P_2(s) = \frac{1}{(s+1)^4} \tag{6}$$

$$P_3(s) = \frac{e^{-s}}{(0.05s+1)^2} \tag{7}$$

In selecting the plants, we were inspired by the papers [5,17,18]. In contrast to our previous work [16], this time the simulation of the plants took place in the PLC using the LSim library developed by Siemens [19]. This meant that there was no need for additional signal acquisition equipment (e.g. a DAQ card) or software for simulating control objects (e.g. Matlab). The function blocks of the LSim library (version 3.0.0) as well as the function block of the PID algorithm (PID_Compact version 1.2) were called in an OB30 cyclic interrupt executed every 20 ms. Data collection was carried out using the trace tool available in the TIA Portal software. The sampling of all signals, i.e. the setpoint y_{ref}, the controller output u and the object output y, was performed with each call of the cyclic interrupt OB30, i.e. every 20 ms.

Identification was always started when a steady state was reached at which the u_0 and y_0 signals were 50%. The amplitude of the excitation a was 10%. The time T_p was chosen automatically and varied depending on the plants under testing. It was the time counted from the start of the experiment until the output signal value $y(T_p) = 1.1y_0$ was reached. Since plants P_1, P_2 and P_3 had a gain of $K = 1$ this was the value $y(T_p) = 55\%$ in all cases. The selection of controller's settings was performed using the Approximate M-constrained Integral Gain Optimisation (AMIGO) tuning rule [15]. A single method was used to eliminate the influence of the tuning method on the final results. According to the AMIGO rule, the PI controller parameters are calculated using the equations:

$$K_p = \frac{0.15}{K} + \left[0.35 - \frac{LT}{(L+T)^2}\right]\frac{T}{KL} \tag{8}$$

$$T_i = 0.35L + \frac{13LT^2}{T^2 + 12LT + 7L^2} \tag{9}$$

where: K_p – controller gain, T_i – integral time.

The PID_Compact function block was used in the project. The manufacturer provides the following transfer function of the controller [20]:

$$u(s) = K_p\left[\left(by_{ref} - y\right) + \frac{1}{T_i s}\left(y_{ref} - y\right) + \right.$$
$$\left. + \frac{T_d s}{aT_d s + 1}\left(cy_{ref} - y\right)\right] \tag{10}$$

where: b – proportional term weighting, y_{ref} – set point, a – derivative delay coefficient, T_d – derivative time, c – derivative term weighting.

We set the values of coefficients a, b, and c to a constant value equal 1. Due to the use of PI algorithm derivative time was $T_d = 0$. To compare results of calculated controller parameters three scenarios were prepared: step change in the set point, trajectory tracking, and load disturbances. Figure 2 shows changes of set point signal in all scenarios. In the first case, step change of set point was applied in the 10th second to a value of 70% and the next step was applied in the 110th second to a value of 30%. The test lasted 210 s. In the second scenario, the set point was changed according to trajectory of response of the first order system $(5s + 1)^{-1}$ to step change to value of 70%. In the 100th second another trajectory was applied. It was response of the first order system $(25s + 1)^{-1}$ to step change to value of 30%. The test lasted 250 s [16]. In the last scenario, the set point was 50% and did not change during the test. The experiment started when the steady state was reached. Next, in the 5th second the load disturbance of value of 10% was applied to a plant input, i.e. controller output signal u. The test lasted 150 s.

The obtained measurements of the plant output y and the set point y_{ref} were used to assess the control quality. For this purpose, the integral absolute error (IAE) index was used, a lower value of which indicates a higher quality of control. A description of other control quality indexes can be found in the papers [21,22]. The index IAE is calculated with the formula

$$IAE = \int \left|y_{ref}(t) - y(t)\right| dt \tag{11}$$

RESULTS

Figure 3 shows the identification process using the doublet-pulse method and Table 1 shows the parameters of the obtained models. Models M_1, M_2 and M_3 corresponded to plants P_1, P_2 and P_3, respectively. For comparison, we have also included the table with the the results of identification by the Method of Moments from another paper [16]. The pulse duration T_p was 0.84 s for plant P_1, 3.68 s for plant P_2 and 1.1 s for plant P_3. Based on the model parameters, the controller parameters were selected according to the AMIGO tuning rule described before. The PI controller parameters for plants P_1, P_2, P_3 are shown in Tables 2-4, respectively. These tables also contain the IAE quality index values for each test scenario.

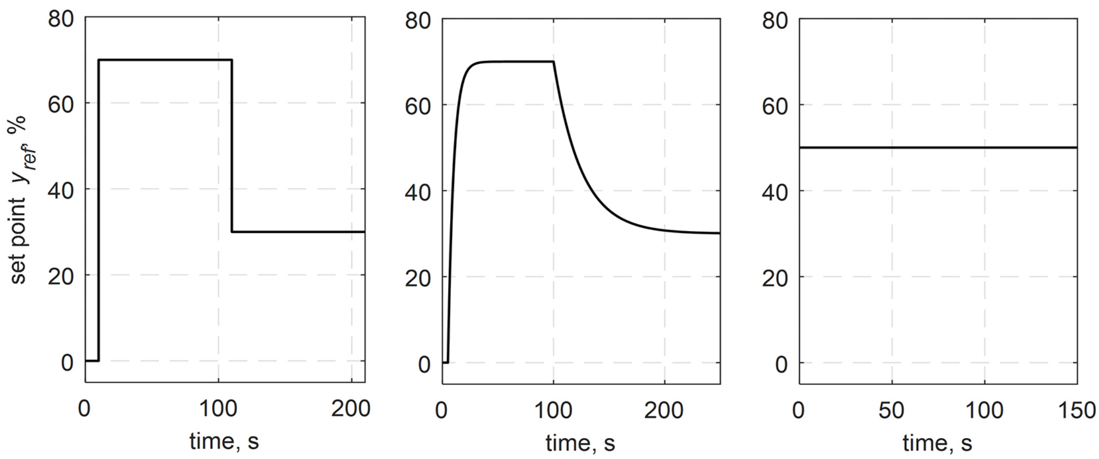

Figure 2. Changes of the set point signal during step change (left), trajectory tracking (middle), and load disturbances (right) test scenarios

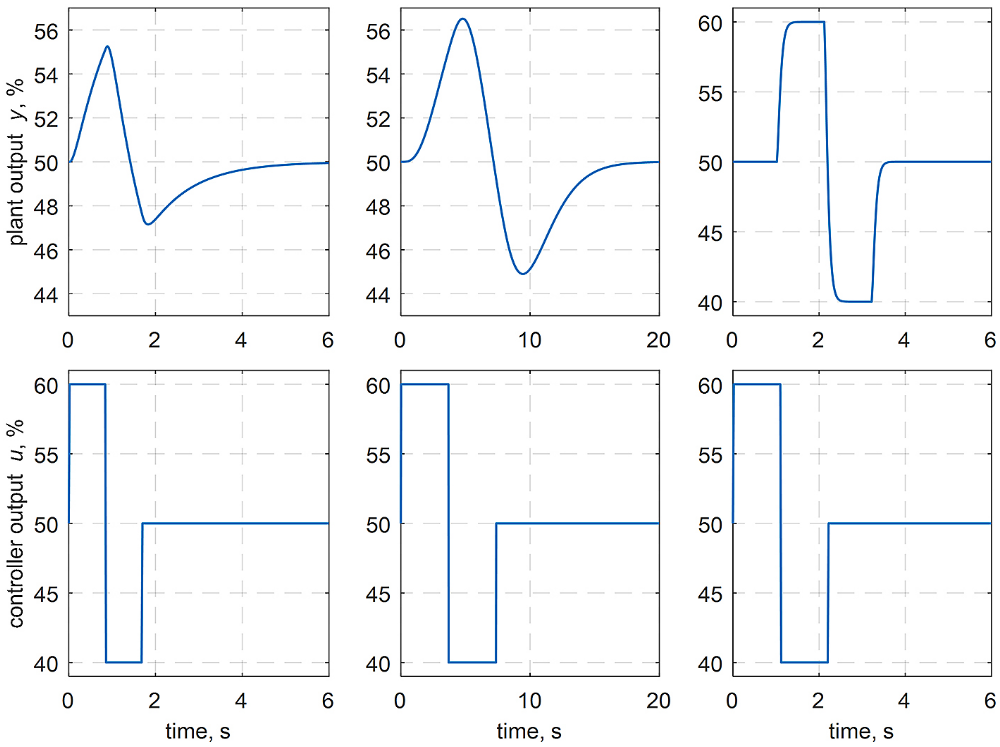

Figure 3. Identification process using the Doublet-Pulse method for plants P_1 (left), P_2 (middle) and P_3 (right)

Table 1. Models coefficients calculated by system identification with doublet-pulse and moments methods

Model	*K* [-]		*T* [s]		*L* [s]	
	DP	MM	DP	MM	DP	MM
M_1	0.97	1	0.8	1.119	0.06	0.12
M_2	0.832	1	4.47	2.168	1.1	1.962
M_3	1	1	1.587	0.117	0.76	1.052

Table 2. Control parameters and control performance assessed for plant P_1

Parameter	Doublet-pulse method	Method of moments
Controller parameters		
K_p	6.39	4.4
T_i [s]	0.28	0.49
Control performance: IAE index		
step	63.6	66.1
trajectory	7.01	14.4
disturbances	0.55	1.12

Table 3. Control parameters and control performance assessed for plant P_2

Parameter	Doublet-pulse method	Method of moments
Controller parameters		
K_p	2.44	0.7
T_i [s]	2.86	2.27
Control performance: IAE index		
step	1178	466
trajectory	680	359
disturbances	128	35.8

Table 4. Control parameters and control performance assessed for plant P_3

Parameter	Doublet-pulse method	Method of moments
Controller parameters		
K_p	0.42	0.25
T_i [s]	0.28	0.51
Control performance: IAE index		
step	578	227
trajectory	97.6	227
disturbances	76.3	20.4

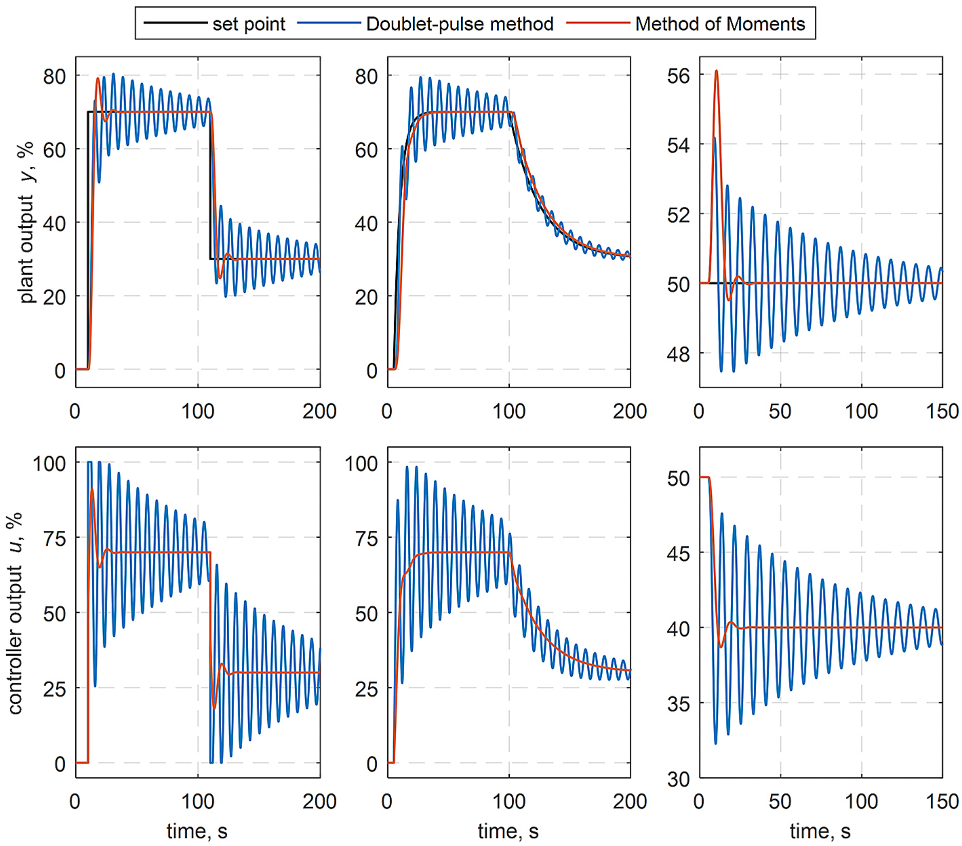

Figure 4. Plant output and controller output for plant P_1 in step (left), trajectory (middle) and disturbance (right) scenarios

Figures 4-6, show the plant output and controller output signals for all the tested scenarios.

DISCUSSION

In the DP method, the execution of the identification experiment does not require reaching a new steady state. This is a major advantage of this method which reduces the time of the identification experiment. The classical step response method, including the MM method, requires the experiment to be run up to a new steady state. For FOTD plants, it is estimated that this requires to wait time equal to 4–5 times the length of the time constant. The exception for this is the P_3 (delay-dominated) plant. The delay of the P3 plant is many times longer than the time constant. The experiment time in the DP method is about twice the pulse time, which in this case depended mainly on the delay. The identification results in Table 1 can be evaluated by comparing the obtained parameters of M to those of process P. All processes P had a gain equal to 1, so the DP method showed a tendency to decrease this parameter. For the M_1 (lag-dominated) model, the underestimation was 3% and for the M_2 (balanced) model, 16.8%. Only for M_3 (delay-dominated) model, the gain

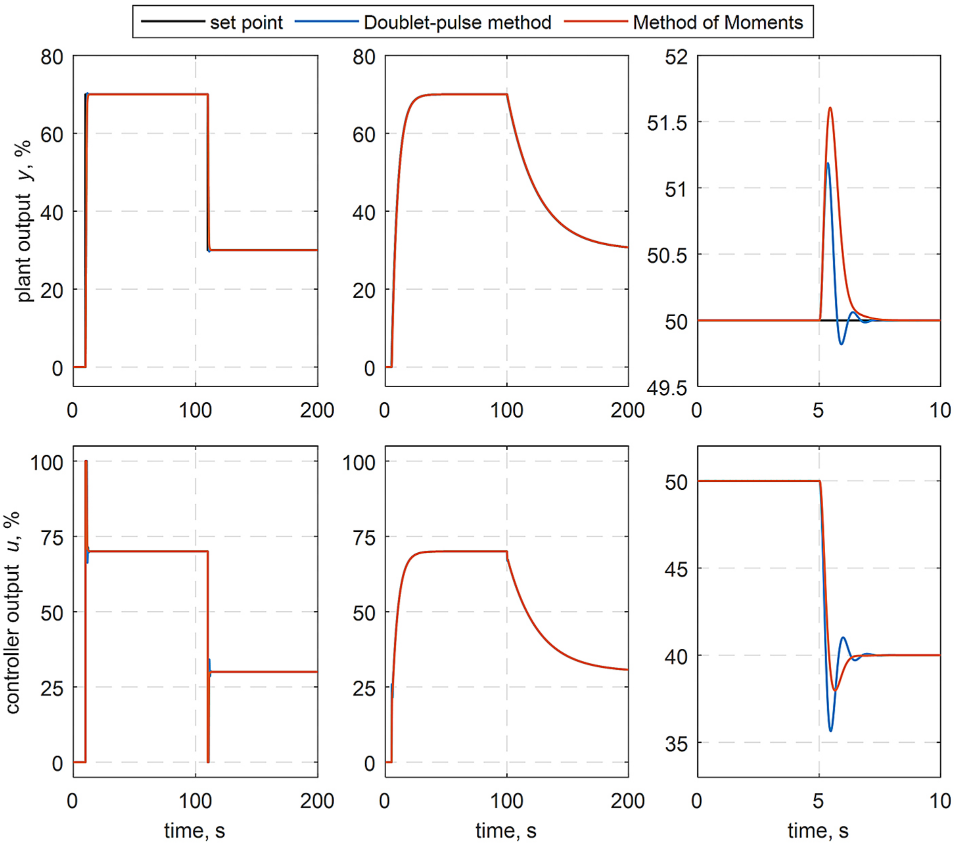

Figure 5. Plant output and controller output for plant P_2 in step (left), trajectory (middle) and disturbance (right) scenarios

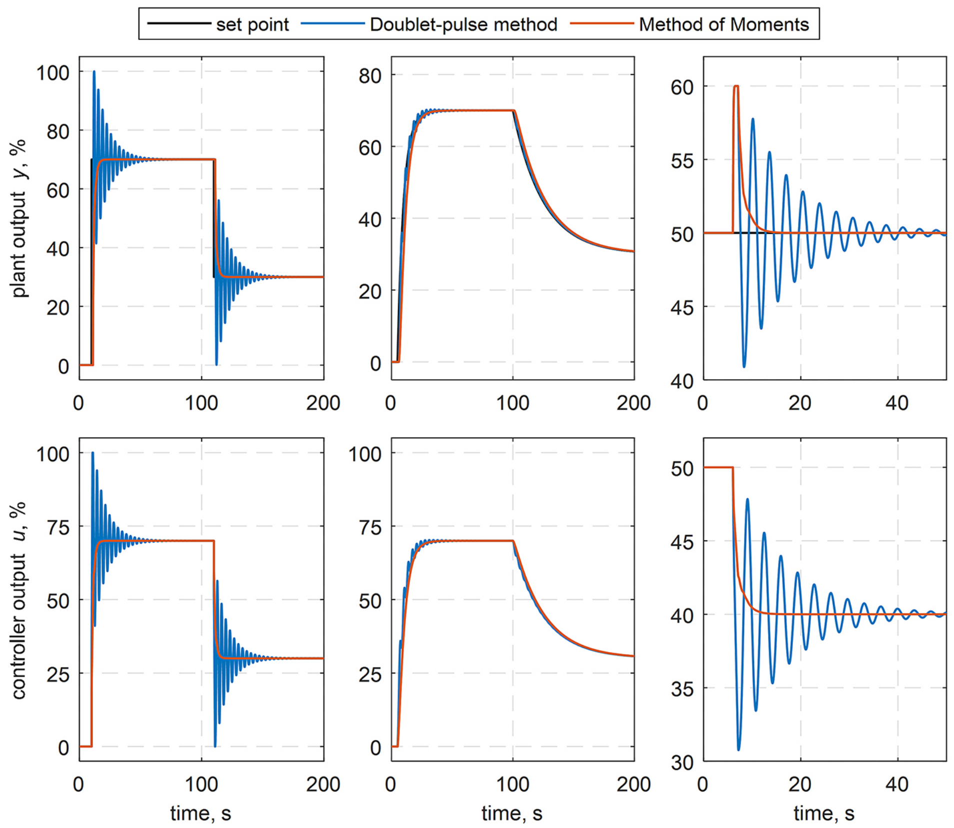

Figure 6. Plant output and controller output for plant P_3 in step (left), trajectory (middle) and disturbance (right) scenarios

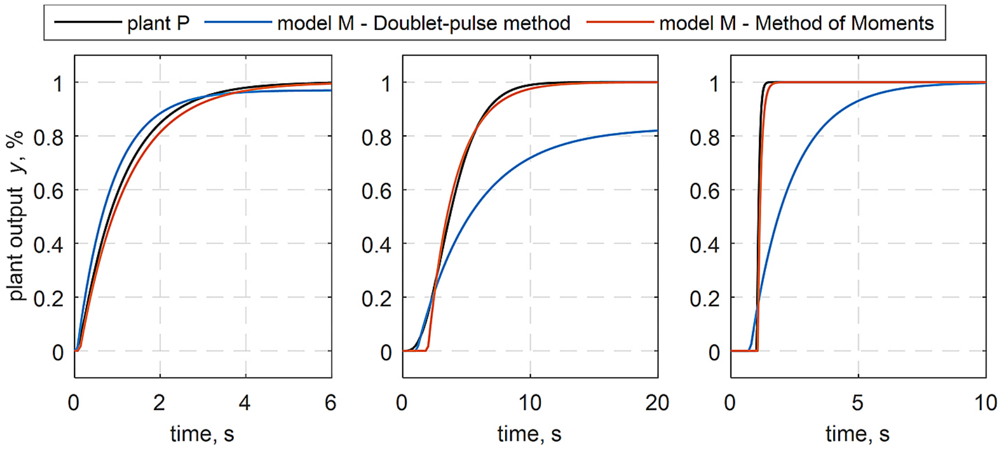

Figure 7. Comparison of the step responses of the P_1 (left), P_2 (middle) and P_3 (right) plants with the M_1-M_3 models obtained by the DP and MM methods

was appropriate. On the other hand, in the MM method every model's gain was estimated correctly. Evaluating the correctness of the estimation of the time constant T and delay L is more difficult due to the fact that the P_1-P_3 plants are of higher order. The comparison may be simplified by the step characteristics shown in Figure 7. The time constant of the model M_1 in the DP method is underestimated, while in the MM method it is overestimated. The values of the time constants are similar, but the dynamics of the P_1 plant is reflected in a better way in the case of the model obtained with the MM method. In the cases of M_2 and M_3 models, the time constant in the DP method is too large. The differences in the values of the time constants are significant. For the M_2 model, the time constant in the DP method is twice as long as in the MM method, and for the M_3 model, it is over thirteen times longer.

The largest variation in delay was observed for the M_1 model. The delay in the MM method was twice as long as in the DP method. However, in both cases the delay values were small and they are practically invisible on the characteristics. For the M_2 model, the delay estimated in the DP method better reflects the dynamics of the plant. The delay in the M_2 model in the MM method is too long. On the other hand, for the P_3 plant, the variations in delay values are smaller, nevertheless the delay estimation is more accurate in the MM method. Based on the IAE index values (Tables 2-4), it can be concluded that the DP method had better control performance than the MM method only for the lag-dominated plant P_1. In the scenario I (step change) the difference in the IAE index value was not significant and amounted to 3.8%. Much larger differences were observed in the other two scenarios (trajectory and disturbance), standing at 51.3% and 50.9% respectively. The values of the IAE index for the P_2 plant control system were lower for the MM method. The largest differences in index values were observed for the disturbance scenario, i.e. 79.8%, and the smallest for the trajectory, i.e., 47.2%. In addition, regardless of the test scenario, no stabilization of the output signal y was achieved in the DP method within the assumed experimental time. The results for the P_3 plant are ambiguous. On the one hand, the MM method provided higher control performance in the step and disturbance scenarios. The difference was 60.7% and 73.3%, respectively. The output signal y showed strong oscillations, which were dampened within the assumed test time. On the other hand, in the trajectory tracking scenario, the DP method performed better. The IAE value was 57% lower with respect to the MM method. Also in this case, the output signal y oscillated during the transient state.

CONCLUSIONS

The main objective of the research was to implement an object identification method using a doublet-pulse signal in a PLC. The objective was fully achieved. We evaluated the doublet-pulse method in terms of control performance in tests related to the response to a set point change in a step-like manner and according to a trajectory as well as robustness to disturbances. We compared the experimental results with another previously investigated Method of Moments. The experimental results lead to the following conclusions. The MM method identifies the dynamics of control objects of all three classes better. The DP method correctly identifies only lag-dominated plants. The models of lag-dominated and delay-dominated plants obtained in the DP method are characterized by too large values of the time constant. The identification experiment in the DP method is shorter than that in the MM method for lag-dominated and balanced objects. For lag-dominated control systems we recommend the use of the DP method, considering the benefits associated with better control performance compared to the MM method. Our further research will be focused on the comparison of the DP method with the MM method in the identification and control of real objects with different dynamics. We are particularly interested in the question of the effectiveness of the identification process in the presence of measurement noises.

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