An industrial fuzzy PID autotuner based on the relay method

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Abstract. The article analyses a auto-tuning method for a fuzzy PID controller based on the relay experiment. The algorithm was implemented and tested on a real plant for redox agent stabilisation in a paper mill. Experiments have discovered some unsolved, practical problems which were discussed in the paper i.e. determination of the ON-OFF parameters, the non-shocked switching from the ON-OFF tuning algorithm into a continues fuzzy PID algorithm.

Keywords: Control Systems, Fuzzy Control, PID Algorithm, Auto-tuning, Relay method

1 Introduction

One of the major problem in control systems is the tuning process of the specific control algorithm. Tuning should optimise the performance of a control algorithm for a given process. Plants incorrectly tuned become unstable, what is potentially dangerous. A common reason for instability is exceeding the very narrow range of acceptable values of adjustable parameters of control algorithms. It is difficult to perform tuning manually or semiautomatically (by an operator) mainly according to non linearity of the controlled plant. From the plant's operator point of view the most convenient way of tuning is an "one push button" solution. Fully automatic tuning methods are proposed in control literature for some time now [6]. PLC and PAC controllers' producers such as GE, Siemens, Bernecker&Reiner and others allow creating control systems with automatic tuning (usually by using a functional block). The problem is that in most cases tuning algorithms are so-called "mixtures" base on one of the method given below and heuristic algorithms, which usually aren't given at all. There are two kinds of experiments in the auto-tuning techniques [6]:

1. open-loop methods:
   - Ziegler-Nichols' Process Reaction Curve method (or the Ziegler-Nichols' Open-Loop method) *Ziegler and Nichols (1942)*
   - Hagglund and Åström's Robust tuning method *Hägglund and Åström (2002)*

   - Skogestad's Model-based method (or: the SIMC method (Simple Internal Model Control) *Skogestad (2003, 2004)*
2. closed-loop methods:
   - Ziegler-Nichols' Ultimate Gain method (or the Ziegler-Nichols' Closed-Loop method) *Ziegler and Nichols (1942)*
   - Relay method (using a relay function to obtain the sustained oscillations as in the Ziegler-Nichols' method), *Åström and Hägglund (1995)*
   - Tyreus-Luyben's method (which is based on the Ziegler-Nichols' method, but with more conservative tuning), *Luyben and Luyben (1997)*
   - Setpoint Overshoot method, *Shamsuzzoha et al. (2010)*
   - Good Gain method; *Haugen (2010)*

Unfortunately applying them into a real time control system isn't an easy task because of several facts : a sophisticated methodology of the tuning preparation - an process engineer has to establish many numerical factors, what demands a detailed knowledge about a controlled process; there isn't an universal method for every plant i.e. every type of plant's dynamic; usually a tuning process is a long term experiment; some of those method aren't suitable to apply them in a real time control mainly because the fact, that calculation need more time than one program cycle; some of those methods are to sensitive in case of disturbances influence. As a result of those remarks we try to develop and implement a method which is able to overcome those disadvantages. Most of these solutions are suitable for classic PID algorithms but not fuzzy PID algorithms, which have become popular in practical applications. The fuzzy PID controller develops a nonlinear control surface which is more suitable for nonlinear plants. Some problems might occur in applications of fuzzy PID algorithms in industrial implementation [7]. The tuning process is more complex due to qualitative synthesis i.e. the rule construction, deciding on inference and defuzzification methods and quantitative synthesis i.e. input and output scaling factors setting and membership functions selection for both fuzzification and defuzzification. In the article a methodology of fuzzy PID controller automatic tuning for scaling factors (equivalent to classic PID algorithm parameters) is proposed.

The main idea is based on the relay experiment [2] that is an ON-OFF control algorithm. The conversion from the Åström algorithm to a fuzzy PID algorithm was proposed in [5]. The article analyses practical aspects of fuzzy PID algorithm tuning using a PAC controller. Experiments on a real control plant for redox agent stabilisation show that relay tuning for fuzzy PID algorithms needs to be modified. Some ideas of relay tuning methodology are proposed.

2 State of the art

The fundamental specifications of the tuning algorithm set by the authors are minimum computation time and the ability to work on-line during normal operations of the system. Using the original idea presented in [5] had to be preceded by overcoming a variety of implementing problems arising from practical phenomena existing in real time control systems like dynamic and static nonlinearities, measuring noise and nonstationarity etc. Dynamic nonlinearities of real control plants result in changing the given SP value while the operational point is transformed and can negatively influence control quality. Changing the SP value actually brings the system out of equilibrium into the intermediate state. This situation is critical to a real installation as it can destabilize the control system. That is why when the operating point changes the control algorithm needs to be tuned. Signal noise creates computing difficulties in creating the signal derivative or determining its minimum or maximum etc. Nonstationarity of the system and automation devices (actuators) along with dynamic nonlinearities result in operating condition changes, while these alterations arise from changing physical properties of the system and actuators (i.e. aging process).

The relay method being safe and easy is often used when tuning PID algorithms of the ISA and IND structure. This is especially important in industrial practice where downtime and retooling time has to be minimized and stable functioning is essential. More arguments for the relay method are connected with technology parameters in process control systems:

1. a process in safe plant's shutdown mode is controlled using the ON-OFF method i.e. stabilizing the redox agent in paper mills, reactor temperature etc. in this time the control signal amplitudes do not need to perfectly obey technological requirements. It is usually sufficient to remain within a predefined variability range. This perfectly matches initial tuning conditions of the control algorithm for the tuning happens when the system is in shutdown mode.
2. the tuning process needs to work online because in most cases production capabilities and performance has to be kept up
3. the algorithm shall not require complicated preparatory activities like initial manual parameter setup etc.

For many industrial installations a ON-OFF algorithm being the fundament of the relay method, can be used only to tune settings of the proper PID controller and be turned on when production performance could be low i.e when a production is suspended but installation should be controlled. The information gathered while operating in this mode can be used to gain settings for the PID controller.

3 How the autotuner works

A novel digital controller uses auto-tuning algorithms for immediate controller factors adjustment as a response to a dynamically changing process. The auto-tuning procedure can be run automatically each time the amplitude of the given value is changed. A proposed auto-tuning procedure based on the relay experiment works as follows:

The procedure runs as a state machine with the following states (Fig. 1):

Start — waiting for an action

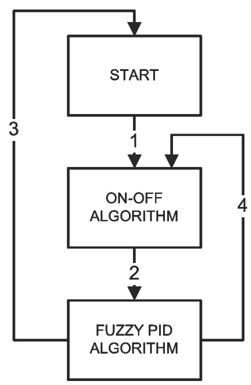

Fig. 1. The tuning procedure of the fuzzy PID algorithm

ON-OFF algorithm — tuning ON-OFF algorithm, relay experiment conduction and factors calculation for a continuous algorithm.
Fuzzy PID algorithm — run the continuous algorithm (fuzzy PID algorithm in this case)

and following transitions:

1 — launch the relay experiment – operator function
2 — launch the continuous algorithm – non-shock transition from the ON-OFF algorithm to the continuous algorithm
3 — stop the continuous algorithm – a safe plant shutdown
4 — relaunch the relay experiment with changed operating point.

The tuning algorithm analyzes the control value (Fig. 2) that is obtained in the closed-loop control system employing a ON-OFF algorithm (Fig. 3). The key points are the amplitude of the oscillation (A) and the oscillation period (T_{osc}) of the control signal. Based on them settings for the PID and PID-like algorithms (e.g. a fuzzy PID algorithm) are calculated by using formulas presented in [6]. The main idea is to bring the control system to the quasi-critical state, as in the Ziegler-Nichols method, but not to the limit of stability, which in general is not safe.

The ON-OFF algorithm executes a periodic generation of a control value $u(t)$ composed of two values: CV_{max} and CV_{min} to the controlled plant causing the controlled value $y(t)$ to oscillate within given limits: form $minError$ to $maxError$. Switching the $u(t)$ signal to a CV_{max} is performed when the controlled error $e(t)$ is lower than $maxError$ and the process is continued until the $e(t)$ amplitude will be equal to $minError$. Then the $u(t)$ signal is switched to the CV_{min} amplitude and is unchanged until the error $e(t)$ is equal to $maxError$. The cycle of switching is repeated as shown in Fig. 2. The switching frequency and oscillation amplitude are dependent on the inner dynamic of the process and the $u(t)$ amplitudes in ON and OFF states.

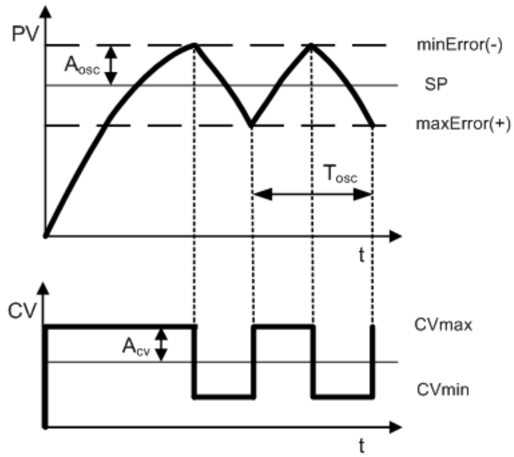

Fig. 2. Control value (CV) and process value (PV) signals in the control system with ON-OFF algorithm

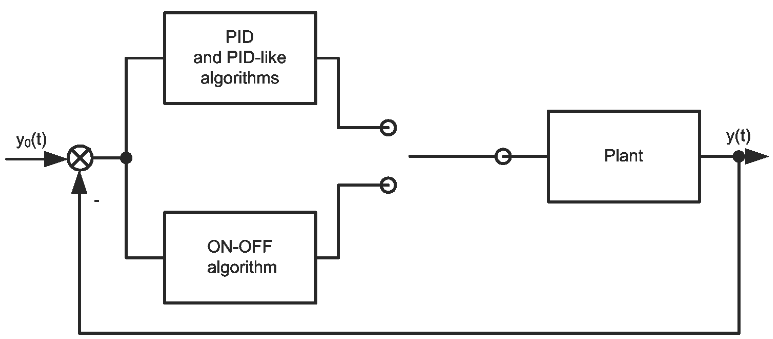

Fig. 3. An idea of the autotuner in the control system with PID and PID-like algorithms [3].

The main problem with a practical implementation of the ON-OFF algorithm (static characteristic of the algorithm: 4) is to specify the control value (CV) amplitudes for ON (CV_{max}) and OFF (CV_{min}) states guaranteeing safe operation of the controlled plant. Safety is ensured when the controlled signal (PV) does not exceed the range between $minError$ and $maxError$. Error values are technological plant limitations and are given by a technologist. In the literature the only given method for setting CV_{max} and CV_{min} amplitudes is setting them arbitrarily. If those values are incorrect in real implementations then the upper range value i.e. $minError$ never is reached or is exceeded. Moreover the controlled value PV should spread symmetrically around the SP. The selection of CV_{max} and CV_{min} amplitudes for a plant with given requirements is a non trivial task. Unlike a system described in [5] real systems are highly dynamically nonlinear (sensitive to switching the operating point that correspond to CV_{max} and CV_{min} amplitudes).

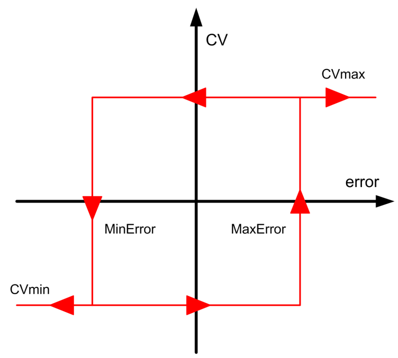

Fig. 4. A static characteristic of the ON-OFF control algorithm.

In case of the ON-OFF algorithm implemented on the plant with unknown dynamics a good solution is setting an CV_{max} amplitude to a small value e.g. equal to an amplitude of a given value. Then the CV_{max} amplitude is increased until the controlled signal reaches a steady state (CV_{min} state). A derivative of the controlled value is applied for steady state detection. The derivative expresses a tangent of the signal angle and when it is close to 0 the system begins to reach a steady state. Experiments show that the application of a static gain to a given steady-state for a default CV_{max} amplitude is advantageous. The static gain value allows CV_{max} and CV_{min} amplitudes estimation resulting in the controlled value spreading symmetrically around the given value. This estimation assumes system linearity (Fig. 5).

When the ON-OFF algorithm is correctly tuned the next problem is to precisely specify the oscillation amplitude (A_{osc}) and the oscillation period (T_{osc}) (Fig 2) for the controlled value that is generally mixed with a measurement noise. The measurement noise might be a source of fault tuning in the presented method and this aspect was omitted in [5]. Signal filtering (e.g. Kalman filtering) used before the scaling factors of the continuous algorithm are set, can be a solution to the problem.

A gain K_u and a period of time T_u can be calculated from A_{osc} and T_{osc} [5], which are used to compute factors for the continuous algorithm:

$$K_u = \frac{4A_{cv}}{\pi A_{osc}},$$

$$T_u = \frac{2\pi}{\omega_{osc}},$$

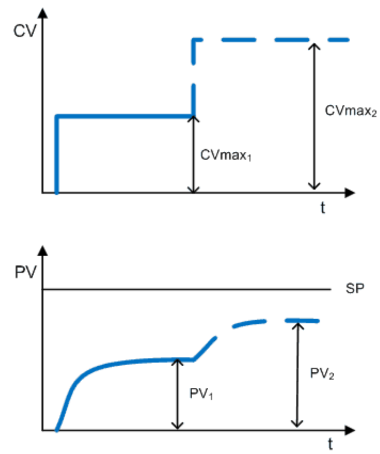

Fig. 5. Estimation of amplitudes CV_{max} and CV_{min} based on a static gain.

where A_{osc} — oscillation amplitude, A_{cv} — relay element hysteresis, ω_{osc} — oscillation frequency.

Formulas for the fuzzy PID scaling factors calculus [3] are presented in Table 1 .

Table 1. Formulas for the fuzzy PID scaling factors calculus [3]

Base	GE	GCE	GU	GCU
K_u, T_u	1	$\frac{1}{4}T_u$	$0.3gK_u$	$1.2g\frac{k_u}{T_u}$

The non-shocked switching to the continuous algorithm should be performed after the scaling factors calculation. The control system with an ON-OFF algorithm is in transition mode that makes the switching complicated. It is easy to lead the system to a steady state when experiments start in initial conditions i.e. all variables are equal to zero. Avoiding overshooting during switching is a technological problem. Non shocked switching in the tuning algorithms is an interesting area for further research.

4 FuzzyPID algorithm synthesis

The first idea for a fuzzyPID algorithm was a three input system. The consequence was a three-dimensional rule base that is non intuitive and difficult to define for a human expert. Li and Gatland (1996) proposed a solution that is a combination of fuzzy PI and fuzzy PD. There are two separate parts for PI and PD with a two inputs rule base each. One more advantage is that both rule bases share the same inputs.

The fuzzyPID algorithm project was created in Matlab-Simulink and tested in the model in the loop mode. Than it was extended by the embedded functions from B&R library to allow the fast prototyping procedure on the PAC controller from B&R [4] (Fig. 6). A detailed description of this idea is given in [7].

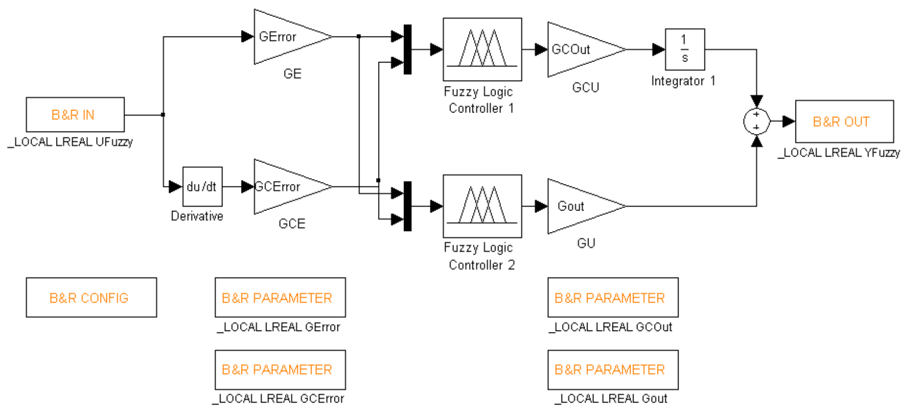

Fig. 6. Model of the fuzzy PID algorithm with embedded functions.

A fuzzification was performed on inputs using triangular membership functions (Fig. 7 (a)). Before fuzzification input signals were scaled to the range $[-1, 1]$ using blocks GE and GCE. A center of gravity deffuzification method is performed using triangular membership functions (Fig. 7 (b)).

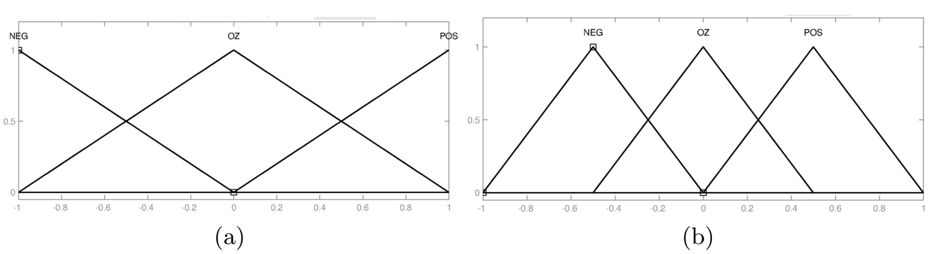

Fig. 7. (a) Membership functions in the fuzzy PID algorithm, (b) a defuzzification function in the fuzzy PID algorithm

Rules are presented in the Table 2 where e — error, ce — error derivative.

Table 2. Rules in fuzzy PID algorithm: inputs: e — error, ce — error derivative, output: U

e/ce	**NEG**	**OZ**	**POS**
NEG	NEG	NEG	OZ
OZ	NEG	OZ	POS
POS	OZ	POS	POS

5 Experiments on auto-tuned fuzzyPID

5.1 Control plant description

The presented tuning algorithm was verified in the redox agent stabilizing system i.e. dispensing of hypochlorite to the the circulating water tank intended for paper machines. The redox factor is the degree of circulating water oxidation. Large quantities of water are consumed in wood and wood-free paper production. Water is transported using pumps and the piping goes through a paper machine. Kilometers of pipes, closed water circuits, high temperature and cellulose pulp creates ideal conditions for either bacteria or fungal rapid growth. Some of these organisms are neutral and do not affect the quality of the final product, however, some of these can impair the quality of production, and even cause failures, gaps and breaks in production. To limit the growth of bacteria it is necessary to use strong oxidizing agents i.e. toxic biocides. Neutralization is particularly important in closed water circuits.

Hypochlorites are very strong oxidizing agents. They react with many organic and inorganic compounds. The reaction removes clots and microbial organisms. The redox agent stabilizer consists of the following components (Fig. 8), according to [1]:

1. redox sensor (QE),
2. redox converter (QT)
3. automatic control unit (FC),
4. controlled device (pump).

5.2 Experimental results

The maim experiment first tunes the fuzzy PID algorithm based on the methodology given in the article for a given set value SP and then tests the controlled system with another set value SP. This approach should confirm the resistance of the controlled system to changing dynamic plant properties via an operating point switch. Fig. 9 shows that the tuning process lasts for about 10 minutes. The reason is the large inertia of the process. It is worth noticing that at the moment of switching form ON-OFF control to a continues fuzzy PID control the Redox_PV controlled signal amplitude drops significantly. The problem of

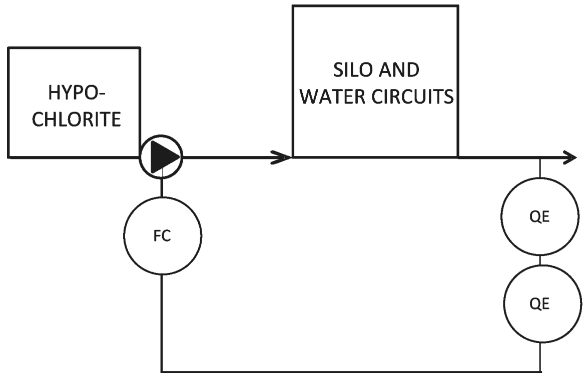

Fig. 8. A simplified diagram of the redox stabilization system with P&ID symbols.

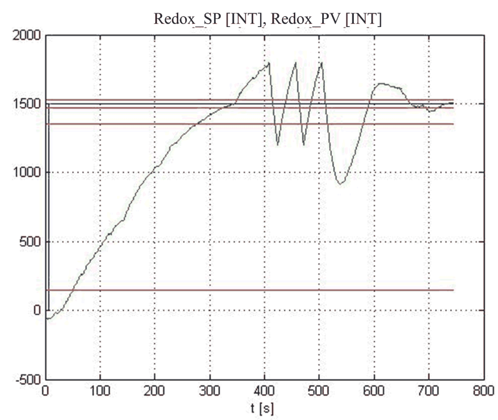

Fig. 9. A tuning process of the fuzzy PID control agorithm.

non-shocked switching is a handicap that should be taken into account in multi-control systems.

Fig. 10 presents a controlled signal Redox_PV with a tuned fuzzy PID algorithm with zero initial conditions. The system can be considered as recovered after approximately 4 minutes.

In the Table 3 measured quality factors are presented.

The next experiment tests the resistance of the controlled system to stochastic disturbances. The PV signal disappearance was examined. Such a PV change can simulate a sensor damage.

After the Redox_PV signal disappears for a short time the fuzzy PID algorithm brings it again to the Redox_SP set point. Summarizing it can be stated

Table 3. Quality factors gathered during experiments on the real plant.

quality factors					GE	GCE	GU	GCU
T_n	T_r	M_p	M_{pp}	eu				
48.3871	218.145	0.197	19.7	0	1	4.08	0.76	0.19

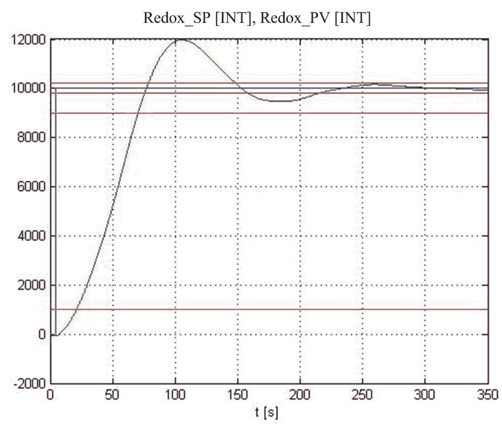

Fig. 10. A step response of the real time plant in the control system with the fuzzy PID algorithm.

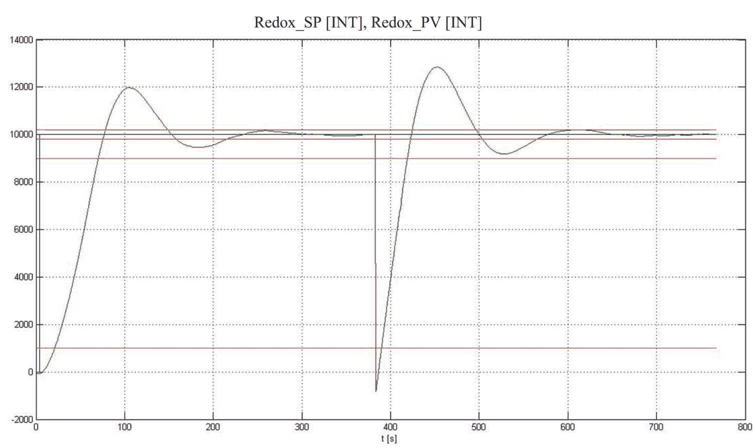

Fig. 11. A robustness test related to the introduction of a stochastic disturbance in the control system with a fuzzy PID controller.

that the fuzzy PID algorithm tuning based on the relay experiment allows for a factor selection resulting in the controlled plant being stable.

6 Conclusions

Based on the survey it was found that the fuzzy PID algorithm is an excellent solution for systems where the emphasis is on small overshoot, and the recovery time is not very important. In case of the redox agent stabilization it is a good solution ensuring that the desired oxidation level is reached in the circulating water without the risk of an excessive overshoot of the controlled signal.

The tuning fuzzy PID algorithm based on the relay experiment allows factors adjustment i.e. scaling input and output factors in a way that ensures stable operation and minimizes overshoot. The result of the research was a development of an automated parameters selection for the ON-OFF algorithm i.e. the ON and OFF states amplitudes of the control value. The ON-OFF algorithm is the basis for the relay experiment. The only concern is a significant disruption in the operation of the control system at the time of switching from tuning to continuous control.

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