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Fuzzy Adaptive Control System of a Non-Stationary Plant

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Abstract. This paper proposes a hybrid fuzzy PID control logic, whose tuning parameters are provided in real time. The fuzzy controller tuning is made on the basis of Mamdani controller. In addition, this paper compares a fuzzy logic based PID with PID regulators whose tuning is performed by standard and well-known methods. In some cases the proposed tuning methodology ensures a control performance that is comparable to that guaranteed by simpler and more common tuning methods. However, in case of dynamic changes in the parameters of the controlled system, conventionally tuned PID controllers do not show to be robust enough, thus suggesting that fuzzy logic based PIDs are definitively more reliable and effective.

1. Introduction

Nowadays the conventional proportional-integral-derivative (PID) controllers are the most widely used for process control in most of the industrial plants. The success of PID control logic can be attributed to the achievement of simple structures of automatic control systems (ACS) and its effectiveness for linear systems [1, 2]. There is a wide variety of PID controllers tuning rules: the Ziegler-Nichols rule [3], the magnitude optimum method [4], the direct synthesis methods [5], the Internal Model Control methods [6], the minimum error integral criteria [7], the iterative feedback tuning method [8], the virtual reference feedback tuning method [9], the approximate M-constrained integral gain optimization method [10], AMIGO method [11] and others. The required quality of a PID control system can be achieved by means of a variety of tuning rules once a linear model of the controlled system and a criteria for the assessment of the control performance are chosen.

Usually the conventional PID controller is not effective for complex dynamic systems. The complex dynamic systems are those systems with non-linear static characteristics, i.e. those systems that are described by differential equations with time-varying parameters. This feature essentially complicates the design and analysis of PID-based control systems and decreases their control performance.

A number of researchers have conducted studies to combine a conventional PID controller with a fuzzy logic controller (FLC) in order to achieve a better control quality in ACS rather than the one guaranteed by conventional PID controllers. The idea of using fuzzy sets is successfully applied, for the first time, in the control of a dynamic plant developed by Mamdani and Assilian. Currently, there are different types of FLC, but a PID-based FLC is the most common and practical for applications to

ACS [12]. Such FLC is equivalent to a conventional PID controller for the input-output structure [13]. PID-based FLC may be constructed by sequentially incorporating FLC and PID controllers or paralleling PID and FLC (PID with an adapter based on FLC). Moreover, the use of FLC logic makes it easy to add nonlinearities and additional input signals to the control law, that, in turn, allows to apply PID-based FLC to complex dynamic systems.

The purpose of the research is to develop a method of synthesis for low-level ACS (relative to HRT), which will provide the required control performance also in the presence of a significant change in the process parameters and several step disturbances with unknown amplitudes and durations. A Low-level ACS must fulfill the following limitations: control in the tight real-time mode should be performed with hot standby of the controllers; applied controllers have limited computation abilities which do not allow an extension of the mathematical support functions; for the purpose of control, conventional PID controllers should be employed.

2. Material and methods for the fuzzy adaptive control of a generic plant

The proposed method employs algorisms for the plant identification coupled with fuzzy systems such as Mamdani controllers [14]. The layout of a generic ACS plant is presented in Fig. 1 while a scheme of an adaptive fuzzy controller is shown in Fig. 2.

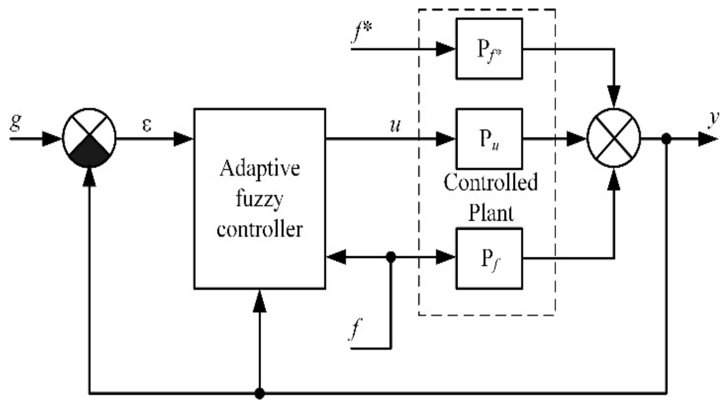

Figure 1. Fuzzy adaptive control system. g : reference signal; f^* : non-measurable disturbance; f : measurable disturbance; P_u : plant control channel; P_f : plant disturbance channel; P_{f^*} : plant non-measurable disturbance channel; y: controlled variable; ε : control error is defined as $\varepsilon = g - y$.

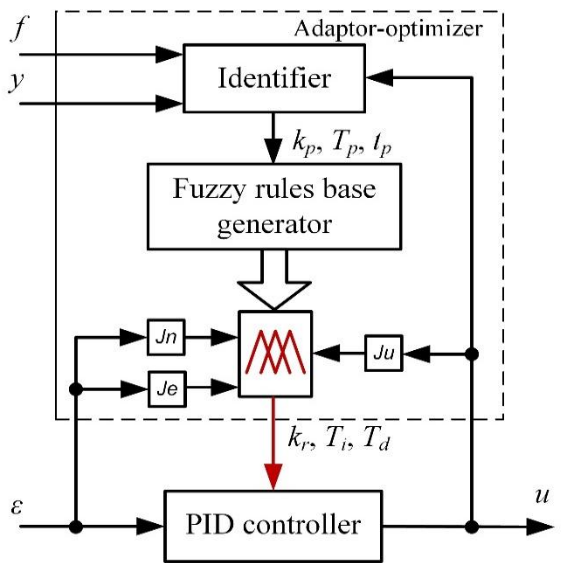

Figure 2. Adaptive fuzzy controller for an ACS.

The optimization problem consists of maximizing or minimizing a functional which plays the key role from the viewpoint of the design of adaptive and optimal control systems. It is addressed here in the following form:

$$\min\left(Je_k + Ju_k + Jn_k\right) \tag{1}$$

where

$$Je_k = \sqrt{\frac{\sum_{j=k}^{k+he}\left(\varepsilon_j\right)^2}{he-1}} \tag{2}$$

$$Ju_k = \sqrt{\frac{\sum_{j=k}^{k+hu}\left(u_j - u_k\right)^2}{hu-1}} \tag{3}$$

Jn_k – the number of control error oscillations in the interval *he*, (2)

where $k = 1,2,\ldots\infty$, ε_j – the control error, u_j – the manipulated variable, *he* – the control error interval, *hu* – the control interval, *j* – the index of time sampling.

The adaptor-optimizer of the suggested ACS (see Fig.2) includes the following blocks: an identifier, a fuzzy rules base generator, a Mamdani fuzzy output controller and *Jn*, *Je* and *Ju* terms calculation engines.

The procedure for calculating the parameters of the PID controller exploits the Mamdani controller with those fuzzy rules previously obtained by minimizing the functional (Eq. 1). Membership functions are generated based on two groups of parameters of the PID, calculated by two different methods.

The first group of PID controller parameters (k_r^{OM}, T_i^{OM}, T_d^{OM}) is calculated by magnitude optimum method. The second group of PID controller parameters is calculated by Ziegler-Nichols. The third group of PID controller parameters is calculated by AMIGO method. In addition, the PID-regulator parameters were determined by means of the method developed in Mikhalevich et al. [15].

The next group of PID controller parameters is calculated by means of the amplitude-phase frequency characteristic (APFC) of the open-loop system $W_{open}(j\omega)$. The PID controller parameters (krmax, Timax, Tdmax), corresponding to the closest to the imaginary axis left eigenvalue of the matrix of the open-loop system Wopen(jω), which is in the range of $-1\cdot(1\div0{,}8)$, are determined.

As a result, by applying two groups of PID controller parameters, the base of the fuzzy rules of Mamdani controller is generated. This basis set of rules and the algorithm required for their evaluation is generated with Matlab.

The PID controller is described by the transfer function Wr(s) reported in expression (4):

$$W_r(s) = k_r + \frac{k_r}{T_i \cdot s} + k_r \cdot T_d \cdot s \tag{4}$$

where k_r – transfer coefficient, T_i – integral time, T_d – derivative time. k_r, T_i and T_d parameters are calculated by means of the Mamdani controller (Fig. 2).

The digital realization of the PID controller (4) is described via a finite-difference form:

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$$\begin{cases} u_j = k_r \cdot \varepsilon_j + C_j + \dfrac{k_r \cdot T_d}{\Delta t} \cdot \left(\varepsilon_j - \varepsilon_{j-1}\right) \\ C_j = C_{j-1} + \dfrac{k_r \cdot \Delta t}{T_i} \cdot \left(\varepsilon_j + \varepsilon_{j-1}\right) \end{cases} \tag{5}$$

where Δt – sampling time.

An adaptive fuzzy controller (see Fig. 2) can be implemented into the industrial software of the process controller (PLC). Adaptor-optimizer can be implemented as a DLL user-library for SCADA systems. It does not require a tight real-time mode and operates asynchronously with a PID controller.

3. Results of the closed-loop transients coming from the application of the ACS

Fig.3 shows the APFC of the plant and the open-loop system. The PID controller is tuned by the magnitude optimum method («Magnitude optimum» line) and the frequency method («Maximum» line). The PID controller is tuned by means of the adaptor-optimizer in the case in which the graph of the APFC of the open-loop system is between «Maximum» and «Magnitude optimum» curve (Fig. 3).

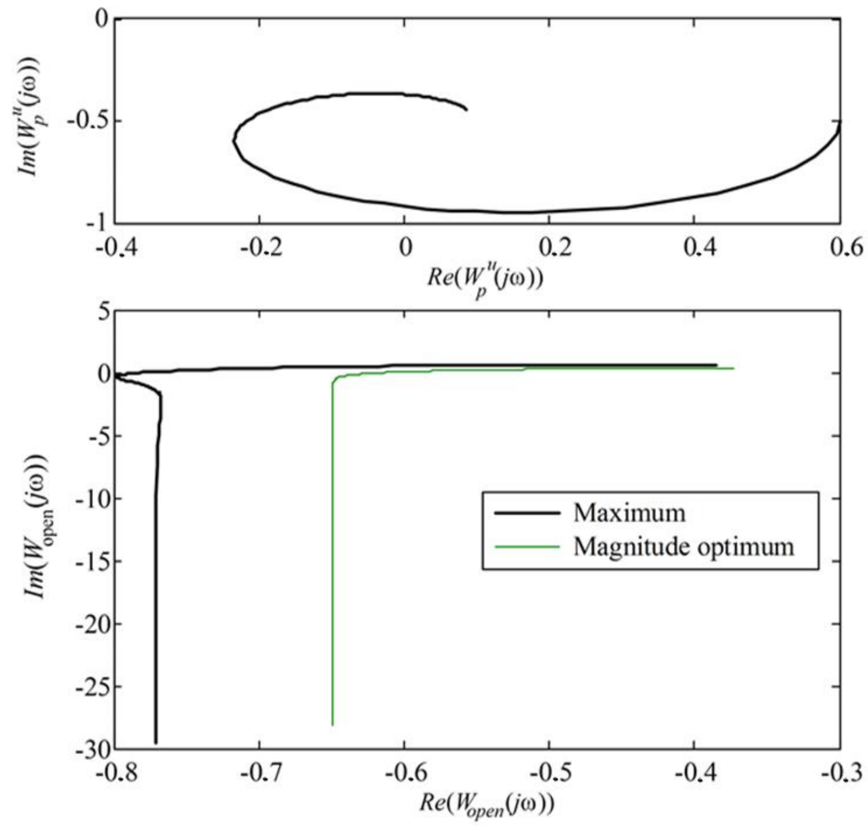

Figure 3. APFC of the plant and the open-loop system

Fig. 4 shows the transient for a 15% step disturbance. The settling time in the suggested ACS (named LF PID in the text) is 10% smaller than in the ACS based on a PID controller tuned by the magnitude optimum method (MO). Moreover, the LF PID method is also compared, in terms of performance, with PID controllers configured using AMIGO and Ziegler-Nichols methods along with the new method proposed in Mikhalevich et al. As Fig. 11 demonstrates, the worst performance is observed in the process controlled with the PID tuned with AMIGO method while the best control quality is obtained when the process is controlled with the regulator set up with the help of fuzzy logic in real time. This visual conclusion is confirmed by the calculated integral quality indicators presented in Table 1.

A dynamic coefficient of control *Rd* is used for the evaluation of the decrease in dynamic error:

$$Rd = \frac{\Delta Y_c^{\max}}{\Delta Y_o^{\infty}} \tag{6}$$

where $Y_c^{\max}$ is the maximum amplitude of one controlled variable in the closed-loop system and Y_o^{∞} is the amplitude of the same controlled variable in the open-loop system.

Fig. 5 shows the transient of the ACS for a 30% step disturbance *f* and a 30% parameters change in W_p^u. The new plant parameters have been calculated at t = 0.48h (see Fig. 5) and LF PID has provided a decrease in *Rd* by 10% by this time in comparison with MO PID. The online adaptation of the PID controller tuning parameters in both the ACSs has made it possible to decrease the settling time by 2, and *Rd* by 3 times in comparison with the non-adaptive system (see Fig. 6). The controlled systems equipped with PID controllers tuned by different methods are analyzed, in terms of dynamic response, under the effect of the same aforementioned perturbation and a change of 30% in the parameters of the process. In this case, the best dynamic response was shown by the system with the regulator tuned with Ziegler-Nichols method, the worst result was shown by the system with the regulator tuned with AMIGO method. This conclusion is also confirmed by the calculated integral quality indicators presented in Table 1.

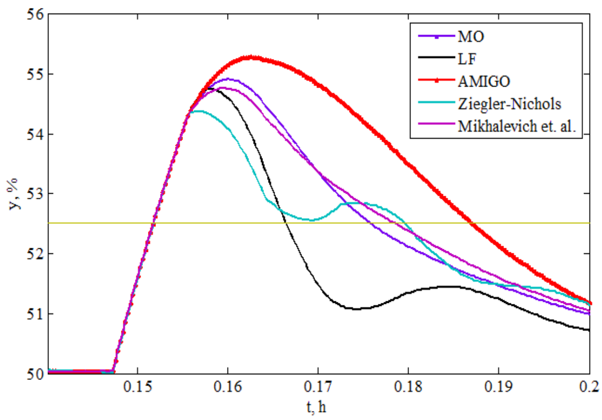

Figure 4. The transient of the ACS for a 15% disturbance.

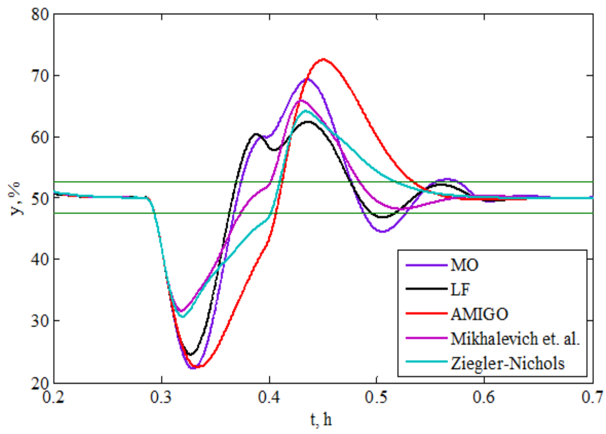

Figure 5. The transient of the ACS for a 30% step disturbance *f* and a 30% plant parameters change.

Table 1. Integral quality indicators

PID controller tuning method	15% disturbance		30% step disturbance on *f* and 30% plant parameters change	
	IAE	ISE	IAE	ISE
LF	0.13	0.31	2.30	32.00
MO	0.16	0.47	2.91	46.81
AMIGO	0.20	0.72	3.69	68.91
Z-N	0.15	0.37	2.20	25.32
Mikhalevich et. al.	0.17	0.47	2.59	34.23

A study on the controlled system stability was conducted too. The process, controlled with a PID regulator tuned by means of either Ziegler-Nichols method or Mikhalevich et al. strategy or by means of fuzzy logic in real time, is selected for the stability test. The achieved transients are presented in Fig. 7. The system, whose controller is tuned using fuzzy logic in real time, proves to possess the best stability. The calculated integral quality indicators assess the previous statement (Table 2).

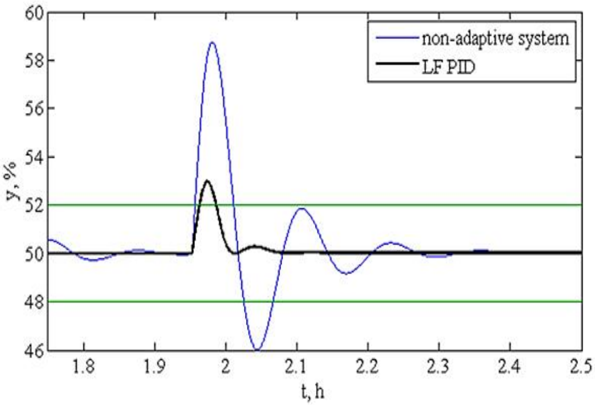

Figure 6. Transient of the ACS for a 15% disturbance and a 30% plant parameters change.

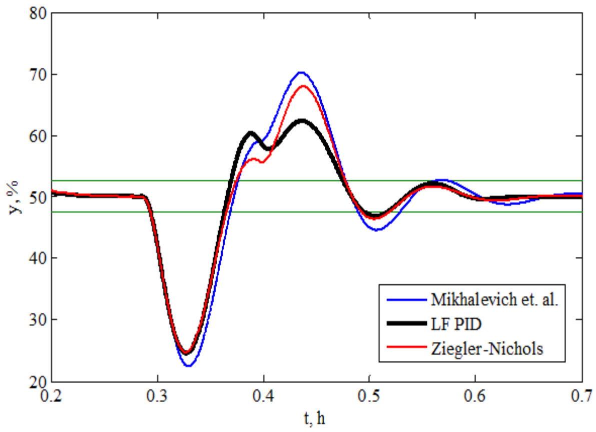

Figure 7. Checking the stability of the control system.

Table 2. Integral quality indicators

PID controller tuning method	30% step disturbance on *f* and 30% plant parameters change	
	IAE	ISE
LF	2.30	32.00
Z-N	2.45	36.19
Mikhalevich et. al.	2.99	47.94

In the near future the research on the suggested method is planned to be carried out in presence of disturbances in more complicated plant models, for example, in models of chemical processes [16, 17], water-treatment networks [18], power control channels of nuclear reactors and others. In addition, a comparison with the model predictive control (MPC) [19] will be investigated.

4. Conclusions

The suggested method of automatic control system synthesis, which is based on the application of a fuzzy adaptor-optimizer, allows developing automatic control systems for generic plants, which provide low sensitivity to the process parameters instability. A continuous process the adaptation of the controller parameters, in cases of significant instability, make the settling time and the dynamic coefficient of control 2-3 times smaller in comparison with a non-adaptive system. The application of the suggested adaptor-optimizer makes it possible to increase the control quality, when a significant error in the plant parameters identification might occur, by 10-15 % in comparison with the adaptive control system based on a PID controller where the controller parameters are calculated by magnitude optimum method, Ziegler-Nichols method, AMIGO method and others. In some rare cases, also the standard tuning methods show good results. However, fuzzy-logic based real-time tuning policies are suitable to be applied in any circumstance, thus being also more flexible and general than conventional offline tuning strategies.

5. Acknowledgements

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