Towards Industrial Autotuning Controller

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Abstract: - In this paper an extended autotuning concept is described. A phase of preliminary identification is detailed. Identification of the process dead-time in the autotuning framework is explained. A PID controller and a filtered predictive PI controller are used for process control. Controller tuning is outlined. Some implementation aspects of the proposed procedure are pointed out. Also, some results of experiments on the laboratory blower process are presented. Experiments have demonstrated that the proposed autotuning controller has satisfactory robustness and good control properties.

Key-Words: autotuning, relay experiment, identification, least-squares method, PID control, FPPI control

1 Introduction

Automatic tuning (autotuning) of PID controllers simplifies and speeds up the task of control system commissioning. Autotuning methods usually employ relay experiments for obtaining data required for the controller design. The method was introduced in [1]. Many modifications have been incorporated in the method in order to improve the characteristics of the designed control system. Modifications include alterations of the original relay experiment [2] and usage of different design criteria. Integral criteria (ISE,ISTE) [3] and gain/phase margin specifications [4] are commonly used as design specifications after the relay experiment. Also, different frequency approaches have been proposed, as part of the autotuning procedure [5]. As a results of such expert efforts, many controller manufacturers have included autotuning as a standard algorithm in their controllers [6].

The main idea underlying the autotuning concept is that the controller parameters are set automatically after a simple identification experiment on an unknown plant. The aforementioned autotuning methods presume the type of the unknown plant. The most important presumptions about the unknown plant are whether it has static or astatic characteristics or whether it has long or short dead time in comparison to the dominant time constants. In order to extend the main idea of the autotuning concept, a preparatory experiment is performed [7]. It determines the type of the plant and sets the parameters for the relay experiment. This procedure allows the algorithm to be used on a larger class of industrial processes, and shortens the time needed for the relay experiment. Furthermore, the additional experiment can be viewed as a standard procedure of reaching the operating point, performed when the plant is started. In [7] a preliminary identification procedure has been outlined, and in the second section a detailed algorithm is given. Additionally, in the second section the tuning of the PID controller and the FPPI controller is described. In the third section some implementation remarks are detailed. Experimental results are presented in the fourth section.

2 Autotuning procedure

The proposed autotuning procedure follows the basic autotuning algorithm explained in [1] and extends it, so that it can be used on a larger class of industrial processes. The extensions include the use of different modified relay experiments and various controllers, depending on the type of the controlled process. Moreover, much attention has been given to the supervision of the course of the procedure in order to make it suitable for industrial use as a full-fledged block in the programmable logic controllers (PLC). Such a feature is very important in the implementation of modern control systems [8].

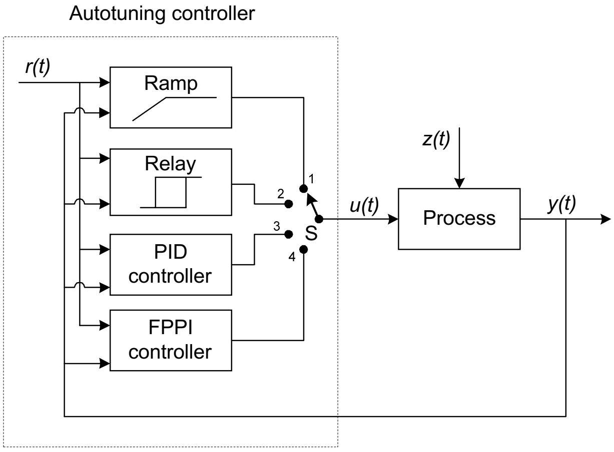

Fig.1 The proposed autotuning controller.

So, the proposed autotuning procedure is divided into three consecutive phases, which are scheduled by the controller after a demand for controller tuning by the user (Fig. 1):

1. Preliminary identification phase (switch *S* is in position 1);
2. Relay experiment phase (switch *S* is in position 2);
3. Control phase (switch *S* is in position 3 or 4).

The phases of the proposed autotuning procedure are detailed in the following subsections.

2.1 Preliminary identification

In the phase of preliminary identification the proposed autotuning procedure determines the type of the controlled process and makes crude estimates of its parameters. This task is accomplished by exciting the process with a ramp signal, and by identifying the process type and process parameters on the basis of its response, using the least squares (LS) procedure, which minimizes the sum of squared errors (SSE) between measured process output data and presumed models.

The slope of the ramp signal is selected by the user according to the expected time scale of the process. The procedure of preliminary identification is supervised by monitoring the control signal *u(t)* and the output signal *y(t)* of the process. If the control signal reaches the upper limit value, the procedure is stopped and repeated with a slower ramp. Additionally, when the output signal does not pass a given threshold in time calculated from the process time scale, the procedure is repeated with a faster ramp. Typical control signal *u(t)* and process output *y(t)* during the phase of preliminary identification are shown in Figure 2.

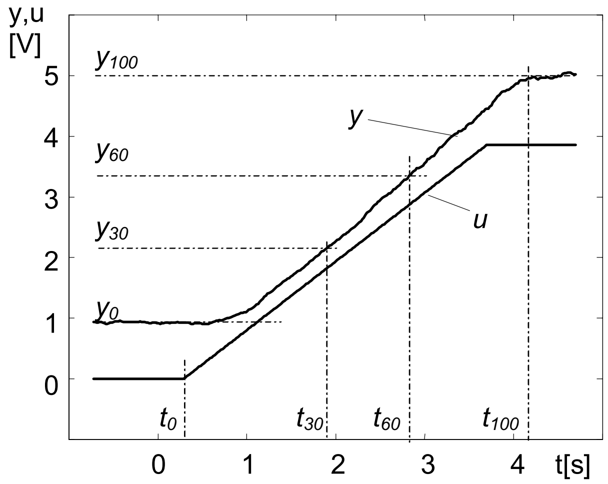

Fig.2 Phase of preliminary identification.

During this experiment values of the process output signal *y(t)* are collected. The collection of the data should start when transients in *y(t)* die out, and it should be stopped before *y(t)* reaches the operating point. The time instant t_{30}, when *y(t)* reaches 30% of the operating range (y_{100}-y_0), can be regarded as suitable for starting data collection, and the time instant t_{60} can be regarded as suitable for ending data collection (Fig.2). At the end of data collection, the data set is fitted to presumed models, the parameters of the models are calculated and the type of the process is determined. Furthermore, the initial parameters of the relay for the experiment are calculated. After the calculations, the process is driven into the operating point y_{100} by a conservative PI controller, which is designed using the model of the process obtained in the preliminary identification. When the process output reaches the desired operating point, the relay experiment is started.

The proposed autotuning controller is based on the supposition that a wide class of industrial processes can be modelled with one of the two typical process models:

Type I model:

$$G_I(s) = \frac{K_1 e^{-sL_1}}{1 + T_1 s}, \tag{1}$$

Type II model:

$$G_{II}(s) = \frac{K_2}{s(1 + T_2 s)}. \tag{2}$$

When excited with a ramp signal:

$$U(s) = \frac{K_0}{s^2}, \tag{3}$$

which is used in this phase of the autotuning procedure, the response of the type I model in the time domain is:

$$y_I(t) = \begin{cases} 0; \ t < L_1 \\ K_1 K_0 \left[(t - L_1) - T_1 \left(1 - e^{-\frac{t - L_1}{T_1}} \right) \right]; \ t > L_1 \end{cases}, \tag{4}$$

and the response of the type II model is:

$$y_{II}(t) = K_2 K_0 \left[\frac{t^2}{2} - tT_2 + T_2^2 \left(1 - e^{-\frac{t}{T_2}} \right) \right]. \tag{5}$$

The transient responses that are present as exponentials in (4) and (5) diminish after some time (5-6 time constants T_1 or T_2). Consequently, the responses (4) and (5) can be approximated with their asymptotes:

For type I model:

$$y_{Ia}(t) = K_1 K_0 [t - (L_1 + T_1)], \tag{6}$$

For type II model:

$$y_{IIa}(t) = K_2 K_0 \left(\frac{t^2}{2} - tT_2 + T_2^2 \right). \tag{7}$$

The SSE, which is minimized by the LS procedure is:

For type I model:

$$SSE_I = \sum_{i=0}^{n-1} [y_i - y_{Ia}(t_i)]^2 , \tag{8}$$

For type II model:

$$SSE_{II} = \sum_{i=0}^{n-1} [y_i - y_{IIa}(t_i)]^2 , \tag{9}$$

where i denotes equidistant time instances when data were collected, and n denotes the total number of collected data.

A simple analysis of the LS procedure [9] shows that the next values should be computed during the data collection:

$$M_y = \sum_{i=0}^{n-1} y_i \ , \ M_{y2} = \sum_{i=0}^{n-1} y_i^2 \ , \ M_{yt} = \sum_{i=0}^{n-1} y_i t_i \ , \ M_{yt2} = \sum_{i=0}^{n-1} y_i t_i^2 \ , \tag{10}$$

$$a_0 = n \ , \ a_1 = \sum_{i=0}^{n-1} t_i \ , \ a_2 = \sum_{i=0}^{n-1} t_i^2 \ , \ a_3 = \sum_{i=0}^{n-1} t_i^3 \ , \ a_4 = \sum_{i=0}^{n-1} t_i^4 \ . \tag{11}$$

Since the relations in (10) and (11) include sums of big values, it is preferable to scale them in order to avoid problems with numerical overflow. Scaling was made in such a way that t_{30} is set to $t_{30}=0$, and the process output values y_i were scaled with the operating range (y_{100}-y_0).

From the computed values (10) and (11), the parameters of the type I model are calculated:

$$K_1 = \frac{1}{K_0} \frac{M_{yt} a_0 - M_y a_1}{a_2 a_0 - a_0^2} , \tag{12}$$

$$L_1 + T_1 = \frac{1}{K_1 K_0} \frac{M_y a_2 - M_{yt} a_1}{a_2 a_0 - a_0^2} . \tag{13}$$

It is important to note that it is not possible to distinguish the dominant time constant T_1 from the dead-time L_1 in the sum in equation (13). This problem is solved with equations obtained in the phase of relay experiment (see subsection 2.2).

A similar calculation is performed for the type II model and parameters K_2 and T_2 are uniquely determined:

$$K_2 = \frac{1}{K_0} \frac{M_{yt2}(a_2 a_0 - a_1^2) + M_{yt}(a_2 a_1 - a_3 a_0) + M_y(a_3 a_1 - a_2^2)}{a_4(a_2 a_0 - a_1^2) + a_3(a_2 a_1 - a_3 a_0) + a_2(a_3 a_1 - a_2^2)} , \tag{14}$$

$$T_2 = \frac{-1}{K_2 K_0} \frac{M_{yt2}(a_3 a_0 - a_2 a_1) + M_{yt}(a_2^2 - a_4 a_0) + M_y(a_4 a_1 - a_3 a_2)}{a_4(a_2 a_0 - a_1^2) + a_3(a_2 a_1 - a_3 a_0) + a_2(a_3 a_1 - a_2^2)} . \tag{15}$$

The next step is to make the decision if the process can be described with type I model or with type II model. It is done using SSE_I and SSE_{II}:

$$(SSE_I - SSE_{II}) / SSE_{II} < x_{threshold} \ . \tag{16}$$

If inequality (16) is satisfied, the process is labelled as type I process, otherwise it is labelled as type II process.

After the calculation of the process parameters, the feedback loop is closed with a conservative PI controller, which drives the process into the desired operating point.

2.2 Relay experiment

The autotuning relay experiment is an automated version of Ziegler-Nichols experiment. It determines the critical gain and critical frequency of an unknown plant, which are the data used for PID controller design. Such an experiment can be viewed as identification of the point on the process Nyquist curve which is positioned on the negative real axis. The identified point of the process Nyquist curve is the intersection of the process Nyquist curve and a line representing the negative inverse of the describing function of the relay element in the Nyquist plane [1]. The describing function of the relay element with hysteresis is:

$$N(A) = \frac{4d}{\pi A^2} \sqrt{A^2 - \varepsilon^2} - j \frac{4d\varepsilon}{\pi A^2} , \tag{17}$$

where ε is the hysteresis of the relay element, A is the amplitude of limit cycle oscillations of output signal and d is the amplitude of the relay output.

From (17) it can be deduced that it is possible to identify other points of the process Nyquist curve through variation of hysteresis ε of the relay element. Other modifications of the original experiment are possible through the use of different dynamic elements, which are connected to the relay. Several modifications of the relay experiment have been proposed with the intention of shortening the experiment, adapting the experiment to the particular class of processes [2] or obtaining additional information about the process from the experiment [5], which is used for PID design.

The relay experiment is performed in the following steps:

1. Setting initial parameters of the relay (d_0, ε_0);
2. Measuring the amplitude and frequency of limit cycle oscillations;
3. Changing relay parameters until limit cycle oscillations with desired characteristics have been achieved;
4. Finishing the experiment and calculating the controller parameters.

For type I processes, the relay experiment is not modified, and it is performed as proposed in [1]. Calculation of the initial relay amplitude d_0 is based on the results of preliminary identification:

$$d_0 = \frac{A_d \pi}{4K_1} , \tag{18}$$

where A_d is the desired amplitude of the limit cycle oscillations.

The amplitude d of the relay element is changed during the relay experiment in an iterative manner [1]. The experiment is carried out until limit cycle oscillations of the desired amplitude are attained.

The next two equations describe the type I process in limit cycle oscillations under relay control [7]:

$$\omega_0 L_1 + \arctan \omega_0 T_1 = \pi \,, \tag{19}$$

$$K_1 = \frac{\pi A}{4d} \omega_0 \sqrt{1 + \omega_0{}^2 T_1{}^2} \,, \tag{20}$$

where ω_0 is the measured frequency of limit cycle oscillations. Since equations (19) and (209) have three unknowns (T_1, K_1, L_1), an additional equation is needed. Using equation (12), the parameter T_1 is evaluated from (20), and the parameter L_1 from (19).

For type II processes, a modified relay experiment is executed. The experiment is modified in order to obtain the amplitude and frequency of limit cycle oscillations in the point of the Nyquist curve, which has a phase angle equal to -135° [10]. A PID controller designed using these data is suitable for the control of type II processes. Modification [2] of the original experiment involves connecting a time delay element to the relay, and changing the value of this time delay. Such a change allows the identification of various points on the Nyquist curve. This modification is equivalent to the experiment with variable hysteresis, but it requires simpler calculation.

The results of preliminary identification given in (14) and (15) are used to set the initial time delay L_0 to:

$$L_0 = \frac{\pi}{4} T_2 \,, \tag{21}$$

and the initial relay amplitude d_0 is:

$$d_0 = \frac{A_d \pi \sqrt{2}}{4 K_2 T_2} \,. \tag{22}$$

The experiment is carried out as described in [2], and when limit cycle oscillations with desired characteristics are attained, the autotuning procedure tunes the PID controller parameters.

2.3 Tuning rules for PID controller

For the type I model with dominant time constant T_1 bigger than dead-time L_1, a PID controller is used. It is tuned according to ISTE criteria [3]. On the other hand, if the dead-time of the process L_1 is bigger than the dominant time constant T_1, a dead-time compensating controller is employed. The use of these controllers as part of the autotuning procedure is described in subsection 2.4.

The PID controller is also used for the control of type II processes. The parameters of the PID controller are tuned according to Kessler-Landau-Voda (KLV) design method [10]. This method is an improvement of the 'symmetrical optimum' design method, and is suitable for the control of type II processes.

2.4 Tuning rules for FPPI controller

PID control is not suitable for the control of processes with a large dead-time. In such cases, dead-time compensating controllers should be used. The Smith predictor is often employed as a dead-time compensating controller. The main problems encountered in the application of the Smith predictor are [11][12]:

- High sensitivity to inaccurate modelling of the process;
- Operational complexity, because it has more parameters to tune then PID controller.

In order to simplify the tuning procedure of the Smith predictor, a restriction on the choice of controller and process model has been proposed in [11]. Such a controller is called predictive PI (PPI) controller and has three tuning parameters. The controller is depicted in Figure 3, with the filter $F(s)$ set to $F(s)=1$.

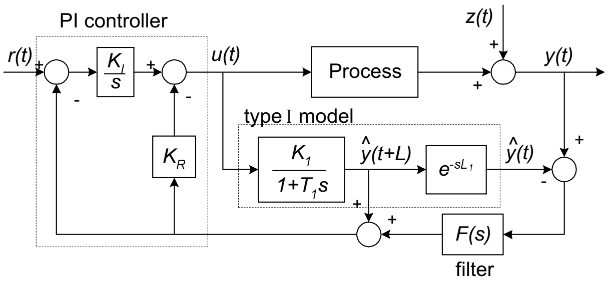

Fig.3 Structure of the FPPI controller.

In the PPI controller the parameters of the PI controller are related to type I model parameters through relations [11]:

$$K_R = \frac{1}{K_1} \,, \tag{23}$$

$$K_I = \frac{K_R}{T_1} \,. \tag{24}$$

In order to increase the robustness of the PPI controller, introduction of a filter into the PPI structure has been proposed [12]. Such a controller is called filtered PPI (FPPI) controller (Fig.3). In order to preserve a simple structure of the PPI filter, F(s) is chosen as the first-order lag with static gain equal to one:

$$F(s) = \frac{1}{1 + T_f s} \,. \tag{25}$$

In [12] the robustness of the FPPI controller is analysed with respect to different values of the filter time constant T_f. As a result of the robustness analysis it is recommended to set: $T_f = L_1/2$.

3 Some implementation remarks

The autotuning procedure was implemented as a function block in PLC Simatic S7 made by Siemens. The discretization time T was set to 20ms.

3.1 Preliminary identification

While testing the autotuning procedure it has been found that the threshold in equation (14) should be set to $x_{threshold} = 0.1$.

Several problems may be encountered while using the LS procedure in the phase of preliminary identification. The operating range (y_{100}-y_0) in which LS identification is made should be much bigger than the amplitude of the noise signal in order to perform it successfully. The most important problem that may introduce errors in calculated parameters is that the collection of data might have started before transients in the process output have diminished. Such a problem can be avoided with the use of a slower ramp function.

3.2 Relay experiment

One of the problems encountered during the relay experiment is the detection of presence of limit cycle oscillations [1]. A crude estimation of time constants in the phase of preliminary identification provides the time scale in which the process should start oscillating. If the process has not started oscillating in the calculated time, the initial relay amplitude is enlarged (e.g. by 10%). This procedure is repeated until the process starts oscillating.

3.3 Control phase

In order to reduce the effects of noise, the amplitude of the noise signal is measured prior to the start of the autotuning procedure. It is used for setting the dead-band of the PID controller in PLC. The value of the dead-band is set to a value two times larger than the measured noise amplitude [5]. Furthermore, a PID controller anti-windup scheme is employed with the intention of avoiding integrator saturation.

The FPPI controller simulates the dead-time of the type I model by using a circular memory buffer in PLC. The size of the memory buffer is proportional to the ratio of simulated dead-time and discretization time of the autotuning controller. If the dead-time is too long, a very big buffer will be required for such a simulation. To avoid this problem, a discretization time exceeding T=20ms is required. The optimal discretization time is calculated on the basis of estimated process parameters, and it is emulated in software as integer multiple of the basic discretization time T.

4 Experimental results

In the first example (Fig.6) the autotuning controller was applied to the control of a laboratory blower process.

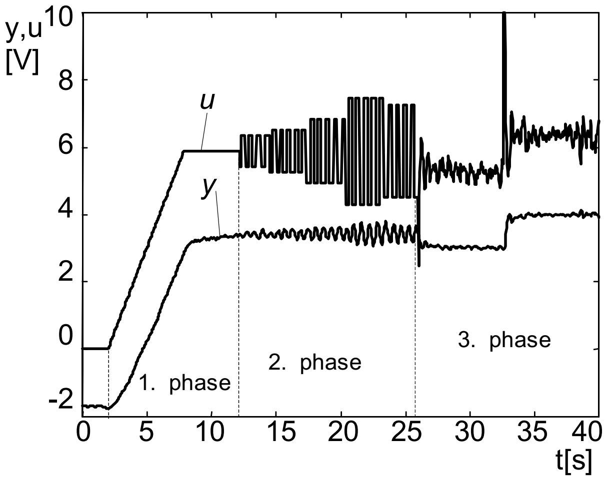

Fig.6 Autotuning experiment on a lab blower plant.

Preliminary identification correctly classified the process as type I process. The relay experiment was started, and the amplitude of the relay element was adjusted until oscillations of the process output signal reached the desired amplitude of A_d=0.5 V. The noise amplitude was measured and the obtained value was 0.07 V. The parameters of the process obtained after the relay experiment were: K_{10}= 0.88, T_{10}=0.58s and L_{10}=0.16s. The parameters of the PID controller were set using the ISTE criterion for data obtained from the relay experiment [3]. The response to set-point change at the time instant t=33s shows that the controller was correctly designed.

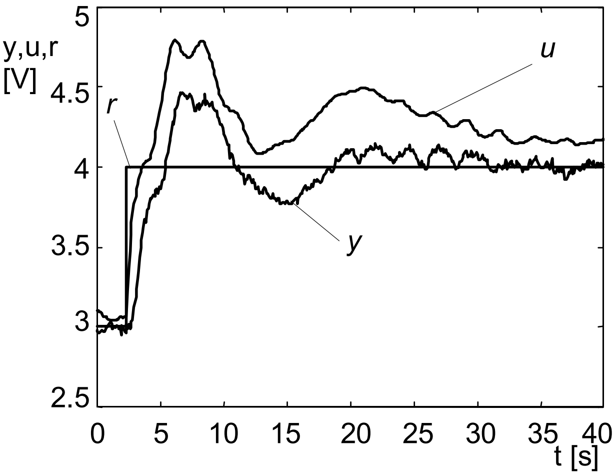

Fig.7 Detail of the control phase with FPPI controller.

In the second example a lab blower process with nominal parameters: K_{10}=0.88, T_{10}=0.58s and L_{10}=3.2s was used. The autotuning was successfully performed and a FPPI controller was started. The waveforms are similar to waveforms in Figure 6. Because of that, only a detail showing the response to set-point change is given in Figure 7. In order to test the robustness of the FPPI controller, it was detuned with an inaccurate model K_1= 0.88, T_1=0.58s and L_1=1.6s. The FPPI controller retained the stability of the control system even with such an inaccurate model.

In the third example (Fig.8) the autotuning controller was used for the control of an astatic process. Responses to set-point change and load disturbance are acceptable.

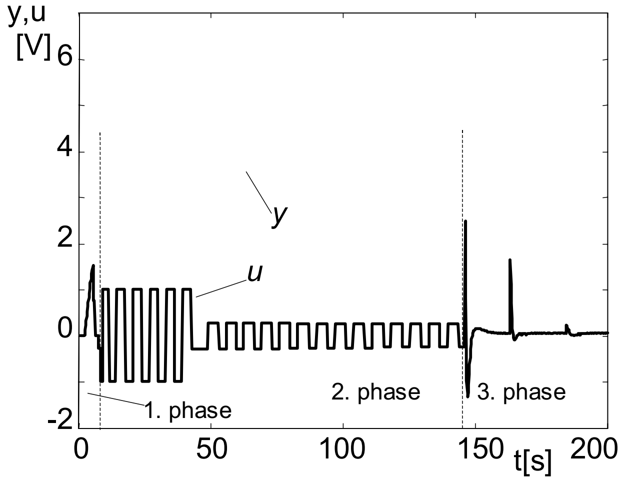

Fig.8 Autotuning on astatic process.

The autotuning procedure has been performed on several laboratory processes. In each test the procedure correctly identified the process type and has set the model parameters to equivalent gain and equivalent time constant.

5 Conclusion

In this contribution the use and benefits of preliminary identification in the autotuning procedure have been explained and detailed. Preliminary identification determines the type of the process and provides a crude estimate of its parameters. These data allow the autotuning controller to be used on a large class of industrial processes. The setup for different relay experiments has been described. The application of the FPPI controller in the autotuning framework has been suggested and experimentally tested. As a results of this application, the autotuning controller can be successfully applied to processes with large dead-times.

Further research will involve adjustment of the autotuning procedure for use in MIMO processes and other types of processes which have not been considered in this paper.

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