Performance Improvement for Quasi Periodical Disturbances in PH Control

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***Abstract*—Proper operation of control systems is essential for achieving good economic results and reducing control effort. The paper is focused on presenting a new application of a well-known concept. The main scope of the paper is a practical presentation of obtaining a minimum process performance index by means of known statistical tools. This is achievable by appropriate selection of the correction value for set-point and the width of the time window of a statistical algorithm. The proposed novel algorithm was successfully implemented in the pilot neutralization process. On one hand, the proposed algorithm is a corrector of the statistical properties of the control error, and, on the other one, of a set point of the control system.**

***Index Terms*—Nonlinear control systems, PI control, Process control, Error analysis, Chemical industry.**

I. Introduction

The issues involved in the analysis of a proper performance of control systems are very important in modern industry in view of the quality of products and manufacturing costs [1]. Nowadays minimizing specific performance index is not usually based on aggressive tunings and has multiple benefits. There are additional parameters which can be regulated for achieving the special objectives of the designer that may lead to reduction of control effort and/or improving the quality of system responses [2]. There are many ways of making this improvement that are learned in universities referring to advanced control engineering, for instance, gain scheduling and fuzzy control [3] or model-based compensation technique [4]. Hence, theoretical and practical knowledge of engineers is constantly growing. Due to the well-established mathematical methods for linear systems also linear control algorithms are popular. The most popular and also used in this work is the PI controller which can be extended with derivative part (PID). This algorithm can be improved by adding input filter based on process model [5] or can be used with iterative auto-calibration method as a good approach to closed-loop shaping [6]. Although PI/PID is very popular, for some difficult control system linear parameter varying (LPV) controller can be used as a possible approach to satisfy acceptable performance and stability for the entire range of operation [7]. Another possible approach is the BBAC methodology (balance-based adaptive control) that can be tuned effectively with similar procedures as PI controller [8]. This algorithm can be applied in a form of flexible function block in professional industrial applications that require additional embed functionalities [9].

Although many valuable control algorithms were proposed many close-loop control systems still work improperly, mostly for two reasons. The first one entails problems with measurement equipment or actuators, the other one is caused by inappropriate selection of tuning/adjustment parameters [10, 11]. Correct diagnostics of a single close-control loop by means of direct analysis of the system by the operator is very time consuming. In consideration of the fact that there may be hundreds or even thousands of such loops within one manufacturing company, the problem seems impossible to be solved [12]. In complex processes there are always deviations, the statistical analysis of which may render information on the occurrence of a deterministic component. The appearance of a specific deviation is frequently characterized by the deterministic behaviour [13]. Instead of testing the system in view of the appearance of new dependencies, it is possible to determine the relations among particular process parameters that verify the correct performance of the system. The weakening of the relations or change in their character may also indicate specific deviations. Therefore, the monitoring of specific relations ratio enables the diagnostics of the process [14]. In general, in the assumed systems, the issue of detecting the reason and place of deviations or failure is by no means very difficult. The proposed algorithm based on statistical information modifies the set-point of controller, resulting in a better maintenance of the process controlled value. It is known in literature that set-point can be changed to improve the system performance [15].

The proposed algorithm was tested on a pilot neutralization installation. The phenomena occurring in the processes, for which pH is an essential parameter may be complex and strongly non-linear [16]. The modelling and control of the pH value is a difficult problem and widely discussed in professional publications. The first good models were devised in the 1970s [17]. Out of many proposals concerning the modelling and control, well-devised models may be found in the works of [18, 19, 20]. Even nowadays the problem has not lost its importance [21] in widely applied biotechnology; accordingly, the selection of the testing model is essential. The first attempts at applying the presented approach were published in 2004 [22]. Since then the algorithm has been modified and tested at the pilot plant installation [23]. This new application of a well-known concept may have significant contribution to the use of control techniques.

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II. Nomenclature

PI	Proportional-integral controller
PID	proportional-integral derivative controller
PV	process value
SP	system set point
SPcorr	PI set point
Kc	controller gain
Ti	integration time
u	controller output value
Tp	sampling of controller and corrector module[s]
$\chi 2$	statistical test
α	level of significance
N	sample size, if Tp=1[s] - width of the time window [s]
S	sum of 1 and -1 series
Corr	correction value
$\chi 2$ max	max value dependent on the α
AES	absolute error sum (performance index)
ASΔu	absolute sum of the change in the control signal
WAES	weighted absolute error sum
MO	maximum overshoot [pH]
ST	settling time [min]
corr	corrected
norm	normalized
$x_1(z,t)$	weak acid concentration at a given point of the mixer [mol/l]
$x_2(z,t)$	strong base concentration at a given point of the mixer [mol/l]
S(z)	mixer cross section
[H+]	hydrogen ion concentration at a given point of the mixer
Ka	acid dissociation constant
Kw	water dissociation constant
C1, C2	input reagent concentrations (acid and base) [mol/l]
F1= const.	input flow of the acid [l/min]
F2	input flow of the base (total) [l/min]
Fm	recycle flows [l/min]
β	denotes the division of the volume of the regions
$F_{2c}(t,z)$	volumetric flow supplying the base along the space variable of the mixer [l/min]
$F_{2d}(t,z)$	F2 in discrete points of feeding [l/min]

III. Materials and Methods

The experiments discussed in the paper were conducted on the pilot neutralization installation consisting of two 500 l capacity tanks with reagent mixers and a reactor with intensive mixing and the capacity of 2 l. The used reagents were a solution of acetic acid with the concentration of 0.0085 [moles/l], and a solution of potassium hydroxide with the concentration of 0.0089 [moles/l]. The pH measurement was taken by pH-meter equipped with ProMinent Dulcotest probe -Type PHEX-112. The reagents were supplied to the reactor by LMI MILTON ROY MODEL CEC933-311TM dozing pumps with the maximal throughput of 30.4 [l/h], 270W [24]. The installation was also equipped with FlexLogix controller manufactured by Rockwell Automation and connected to a computer with RSLogix5000 software tools enabling the programming and monitoring of the controller. The frequency of sampling the process was 1[Hz] (T_p=1[s]). To control the process, standard and commonly used PI (proportionally integral) algorithm was used.

IV. Theory and Calculations

All systems are systems with distributed parameters. Most systems can successfully be approximated by the lumped parameters system. However, due to this, the system may exhibit phenomena that are not explained by the assumed model. The consequence of this is a model with lumped parameters, the error signal with non-Gaussian probability distribution and additionally non-stationary character [16].

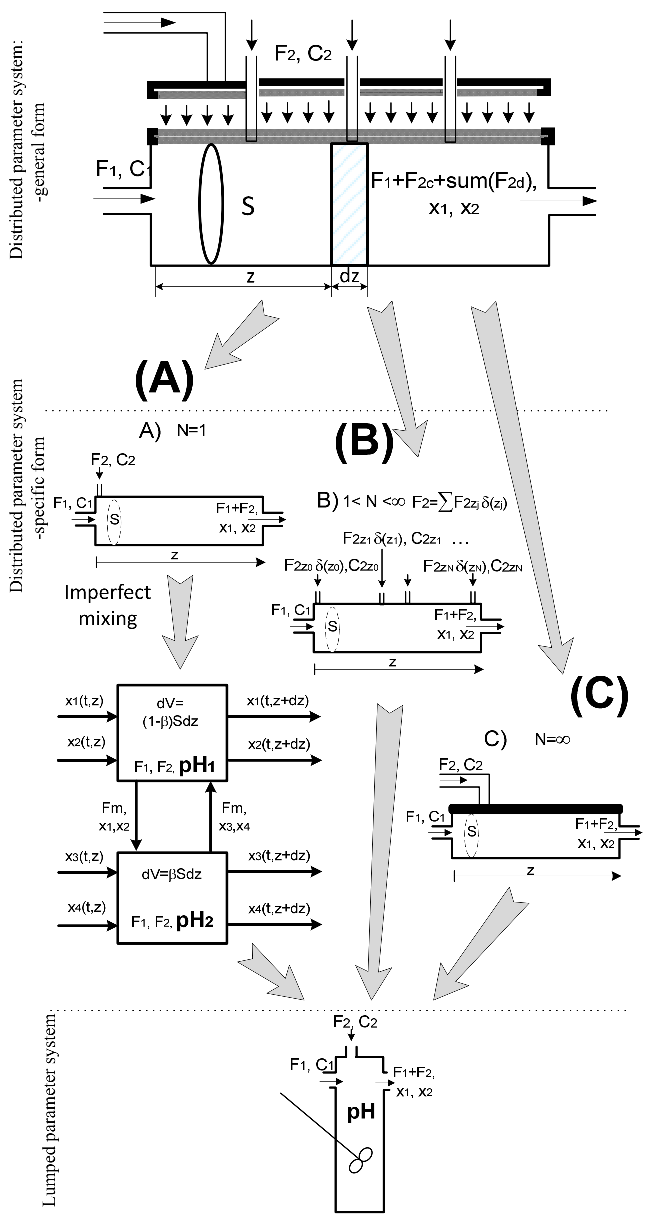


Figure 1. Different approaches to tubular mixer.

pH process can usually be seen as taking place in a tubular reactor (Fig. 1). There are different feed options of reagents (A, B, C). Independent on the possible feeding ways, system can be approximated with lumped parameter system. Considering only the case A, we can assume imperfect mixing in the reactor. In this case, the flow in the reactor can be separated into layers having different chemical properties. The different layers may have different pH values (pH_1 different from pH_2). Assuming lumped parameters model only one pH value is possible.

From mathematical point of view distributed parameter system of tubular reactor with imperfect mixing can be described (eq. 1-8) [16]:

$$\begin{aligned}(1-\beta)\cdot S(z)\cdot\frac{\partial x_1(t,z)}{\partial t} &= -\left(\frac{\partial F_{2c}(t,z)}{\partial z}+\frac{\partial F_{2d}(t,z)}{\partial z}\right)\cdot x_1(t,z)+\\ &-\left(F_{2c}(t,z)+F_{2d}(t,z)+F_1(t)\right)\frac{\partial x_1(t,z)}{\partial z}+\\ &-\frac{\partial F_m(t,z)}{\partial z}\cdot(x_1(t,z)-x_3(t,z))\end{aligned} \quad (1)$$

$$\begin{aligned}(1-\beta)\cdot S(z)\cdot\frac{\partial x_2(t,z)}{\partial t} &= \frac{\partial F_{2c}(t,z)}{\partial z}\left(C_{2c}(t)-x_2(t,z)\right)+\\ &+\frac{\partial F_{2d}(t,z)}{\partial z}\cdot\left(C_{2d}(t,z)-x_2(t,z)\right)+\\ &-\left(F_{2c}(t,z)+F_{2d}(t,z)+F_1(t)\right)\frac{\partial x_2(t,z)}{\partial z}+\\ &-\frac{\partial F_m(t,z)}{\partial z}\cdot\left(x_2(t,z)-x_4(t,z)\right)\end{aligned} \quad (2)$$

$$\beta\cdot S(z)\cdot\frac{\partial(x_3(t,z))}{\partial t}=\frac{\partial F_m(t,z)}{\partial z}\cdot\left(x_1(t,z)-x_3(t,z)\right) \quad (3)$$

$$\beta\cdot S(z)\cdot\frac{\partial(x_4(t,z))}{\partial t}=\frac{\partial F_m(t,z)}{\partial z}\cdot\left(x_2(t,z)-x_4(t,z)\right) \quad (4)$$

β denotes the division of the volume of the regions (layers). The boundary conditions are as follows: $x_1(t,0)=C_1$; $x_2(t,0)=0$; $x_3(t,0)=0$; $x_4(t,0)=0$, whereas, the initial conditions are functions: $x_1(0,z)=x_3(0,z)=fx_1(z)$; $x_2(0,z)=x_4(0,z)=fx_2(z)$. Functions $fx_1(z)$, $fx_2(z)$ initial steady state profiles. Recycle flows F_m are appropriately separated into particular sections it can be assumed that Fm = f(z) in order to consider local imperfect mixing.

$$\begin{aligned}&[H_1]^3+[H_1]^2\left(K_a+x_2(t,z_1)\right)+\\ &+[H_1]\left(K_a\left(x_2(t,z_1)-x_1(t,z_1)\right)-K_w\right)-K_aK_w=0\end{aligned} \quad (5)$$

$$\begin{aligned}&[H_2]^3+[H_2]^2\left(K_a+x_4(t,z_2)\right)+\\ &+[H_2]\left(K_a\left(x_4(t,z_2)-x_3(t,z_2)\right)-K_w\right)-K_aK_w=0\end{aligned} \quad (6)$$

$$pH_1=-\log_{10}(H_1) \quad (7)$$

$$pH_2=-\log_{10}(H_2) \quad (8)$$

Assuming lumped parameters system model have to be reduced to following form (eq. 9-12) (McAvoy 1972):

$$\frac{Vdx_1}{dt}=F_1C_1-(F_1+F_2)x_1 \quad (9)$$

$$\frac{Vdx_2}{dt}=F_2C_2-(F_1+F_2)x_2 \quad (10)$$

pH equation

$$\begin{aligned}&[H^+]^3+[H^+]^2\cdot(K_a+x_2)+\\ &+[H^+]\cdot(K_a(x_2-x_1)-K_w)-K_aK_w=0\end{aligned} \quad (11)$$

$$pH=-\log_{10}(H^+) \quad (12)$$

The final form should contain an error signal e(t) resulting from the approximation (eq.13). Signal e(t) represents model inaccuracy but in case of control e(t) is influenced by poor performance of actuators and the measuring equipment.

$$pH=-\log_{10}(H^+)+e(t) \quad (13)$$

The authors have assumed the thesis that in the case of worsening quality of control due to the quasi periodic disturbances, non-stationary character of the process, poor performance of actuators and the measuring equipment, automatic prevention is possible. Such approach is new and so far has not been discussed in professional publications. The conducted experiments proved that in the case of the neutralization process, which reveals certain non-stationary features and/or quasi periodic disturbances, the proposed approach is feasible. Apart from the mentioned non-stationarity, there are also problems involving exact measurements of pH due to difficulty in estimating its uncertainty [25, 26]. An example of such problems is given in Fig.2. presenting the monitoring of pH value in the system. From a practical point of view, no changes occur because the pH is measured in a solution with constant parameters.

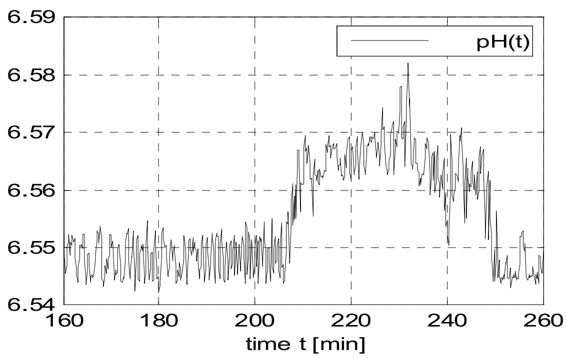
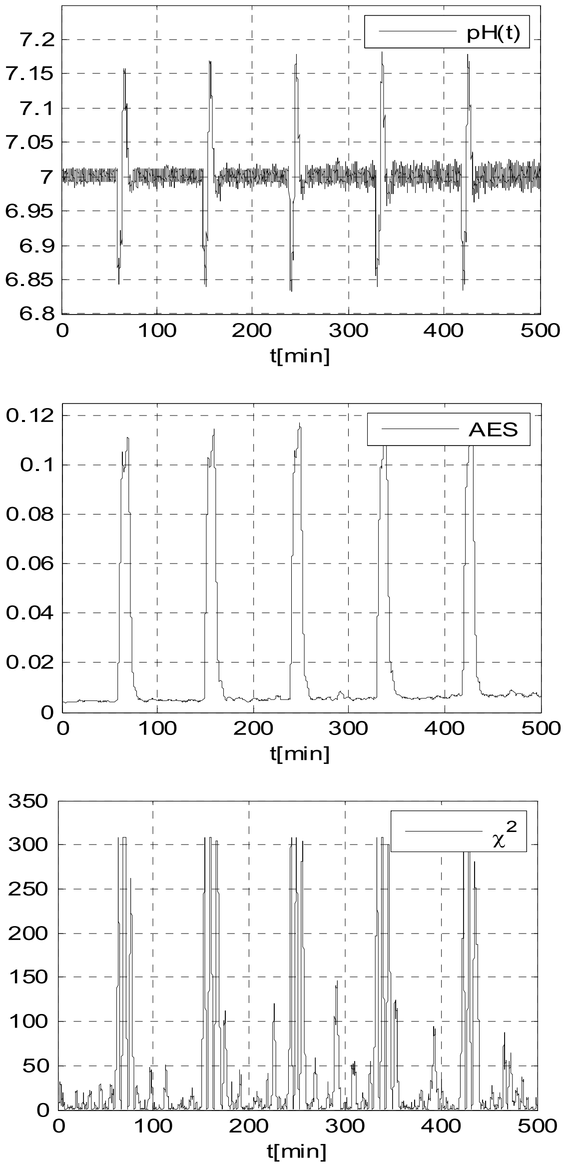


Figure 2. Monitoring of pH values without disturbances.

In a system insulated from disturbances, pH changes may occur (Fig.2) and, even more so, in the not insulated control system, predictable or unpredictable disturbances may take place periodically or quasi-periodically. An example of such situation is presented in Fig.3. An improvement of the quality control ratio is possible by introducing aggressive tunings. However, such solution involves increased maintenance costs of the system, which is not economically advantageous. Another possible approach is the application of advanced phenomenological model based control like internal model control (IMC) which is good solution for system with a well-known model what is true e.g. for synchronous motor drive [27]. When the model is not well known application of advanced model based algorithm is much more difficult. In practice, such algorithm can be ineffective and hard to tune. The authors of the paper have undertaken an attempt at improving the control quality without the necessity of increasing the aggressiveness of tunings. Fig 3b presents the AES performance index calculated in the drift/time window of 310 [s] for a certain neutralization process. A disturbance occurs at the intervals of 1.5 h, which significantly worsens a temporary quality of control. At the intervals between the disturbances the performance of the system is usually satisfactory for conservative tunings, hence, there is no need for any improvements. To formulate the problem from another point of view, it may be stated that for most of the time of the operation of the system, it works appropriately under conservative tuning, enabling economical service. Problems are posed by periodic or incidental disturbances, which, on the other hand, are not frequent enough to justify permanent increase of aggressiveness of tuning in view of economical operation. Accordingly, a question arises: Is it possible to increase slightly the aggressiveness of the operation of the controller under the circumstances of worsened quality of its operation? To provide an answer to this question, two issues should be addressed: how to detect the worsening of the control quality, and, how to increase the aggressiveness of its operation, as there are many possible ways to approach these issues.



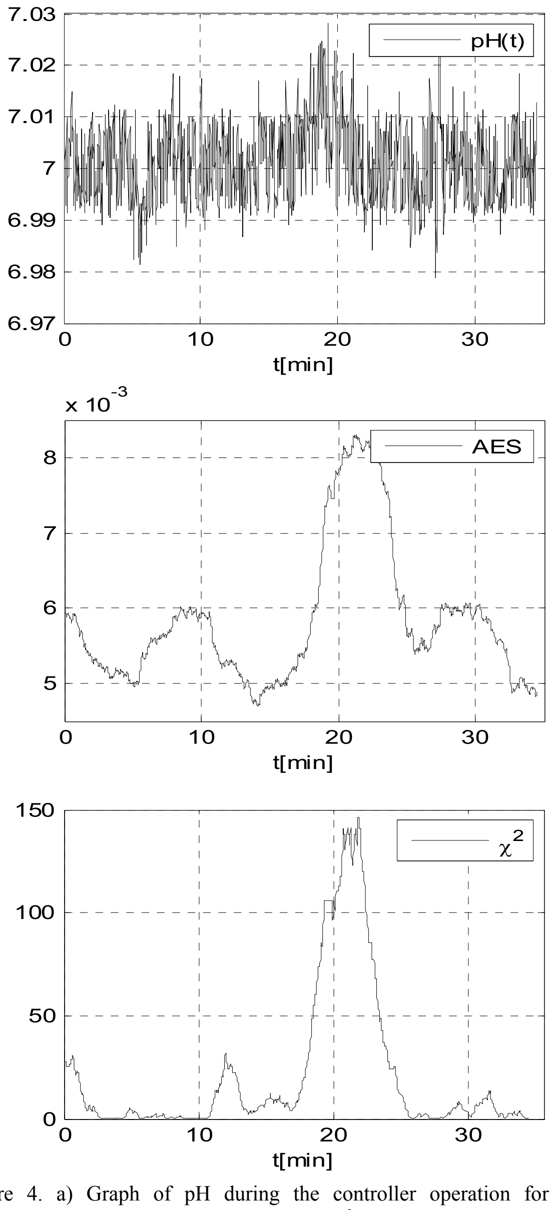
a)

b)

c)

Figure 3. a) Graph of pH during the controller operation for large disturbances, b) Graph of AES, c) Graph of χ^2.

The authors have noticed that the control error is strongly correlated with the value of test χ^2, the graph of which is shown in Fig. 3c. The values of AES and χ^2 are calculated in the time window of the width of 310[s]. Hence, the value of test χ^2 may be used to determine the need for intervention into the system with specified confidence level. Due to the fact that the reason of the occurrence of a disturbance in the system is usually unknown, increasing the aggressiveness of tunings may lead to improvement, yet, it may also evoke to much excessive operation or, in extreme cases, instability, and, more importantly, higher costs of control. Thus, it is difficult to specify when to return to the previous tuning.



a)

b)

c)

Figure 4. a) Graph of pH during the controller operation for small disturbances, b) Graph of AES, c) Graph of χ^2.

The disturbances in the system may have big values (Fig. 3a). Under such circumstances, the χ^2 test may be applied to detect the behaviour of the system. If the disturbances are smaller (Fig. 4a), for example of a quasi-periodic nature, the worsening of the quality control ratio may be observed (Fig. 4b). In such case, the χ^2 test also enables the correct detection of the disturbance (Fig. 4c). It follows from the two above mentioned types of cases, that the χ^2 test is a useful statistical tool for detecting disturbances in the system with appropriate confidence level. According to [28] a typical feature of pH measurement is the occurrence of gross error and the χ^2 test is transferable and useful for pH designation. The second problem requiring a solution is to find such a way of influencing the controller that makes it possible to avoid changes in the aggressiveness of tuning. The authors have decided to alter the set point value at a definite step of change, which enforces an instant change of the control value but does not directly increase the aggressiveness permanently. The designation of the value of specific parameters of the algorithm is discussed below.

On the bases of the conducted experiments, the authors of the paper indicate only the existence of certain mechanisms, which, in the case of non-stationary processes and quasi periodic disturbances, enable an attempt at automatic improvement of the quality of their control. At present stage, there are difficulties in the formal representation of these mechanisms and in stricter determination of the conditions of their applicability. One of the advantages of the proposed algorithm is an opportunity for its cooperation with any controller, from commonly used PI, up to advanced non-linear control algorithms. This feature may appeal to a practicing industrial engineer who wants to prevent the worsening of the control quality. If this thesis is accurate, the quality of control should be improved. The authors of the paper intend to practically illustrate a possibility of looking for the existing minimal value of the performance index.

V. ALGORITHM FORMULATION

In the proposed approach for the application of PI controller, an essential software module is a correction module of the statistical properties of the control error. The general structure of the system is presented in Fig 5. PI controller does not directly receive the set point value that should be maintained in the system, but its corrected value. The difference between the set point and the corrected value results from the operation of the correction module. Hence, the proposed statistical module, from the perspective of control, is the correction module of the set point. The combination of these two features into one algorithm is a new invention of the authors.

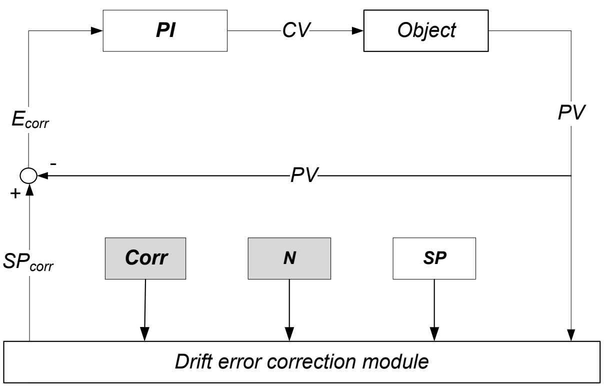


Figure 5. Structure of a close-loop control system with a correction module.

From statistical point of view, it is expected that the deviation shall have the nature of white noise with the mean value equal to zero. If the control errors are not correlated, the quality of control can no longer be improved. In practice, such circumstances never occur, and, accordingly, the analysis of control errors, or, to put things more precisely, their change in time, may render valuable information about the process. It was assumed that the difference between the time of the process value (PV) above or below the set point (SP) should be close to zero with certain variance. If such assumption is true, to assess the quality of control, it is possible to make use of statistical tests such as $\chi^{2.}$ for example to verify the quality of adjustment (to the set point) or to detect essential errors (gross errors) [28]. The used tests may be many-dimensional and enable many aspects of research. So far the results derived by such methods had to be interpreted by the operator, who had to undertake decisions about possible corrections.

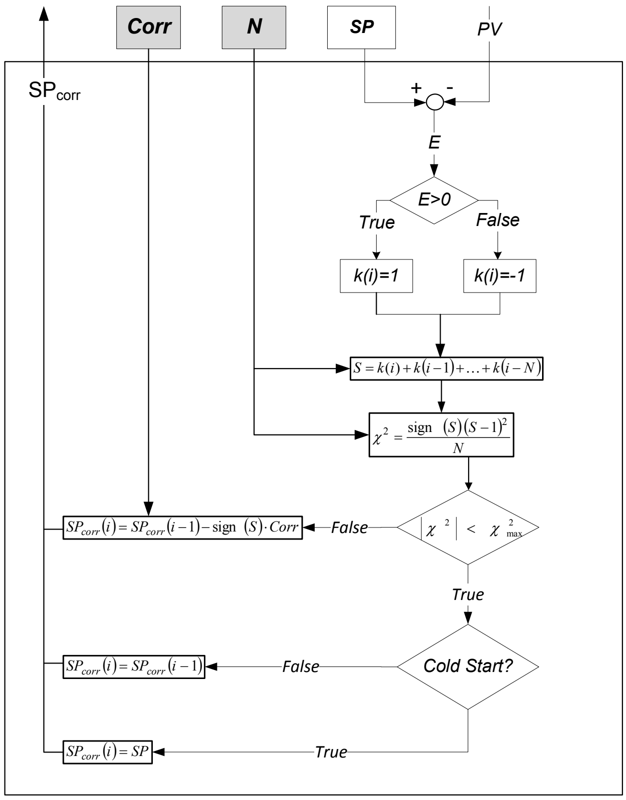


Figure 6. Algorithm description of the drift error correction module.

To automate the process, the information should be obtained faster. Multi-dimensional tests usually require more data to ensure the proper number of classes, and, accordingly, credibility of results. Therefore, to shorten the time of obtaining the results as much as possible, one-dimensional tests were the main focus and test χ^2 of one degree of freedom selected (eq.14).

$$\chi^2 = \frac{(|S| - 1)^2}{N} \tag{14}$$

By means of the test, the difference in times (S) of the presence of PV above and below the set point (SP) in the time scope was determined by the time window with the width of N[s]. It was assumed that the zero hypothesis (difference in times S equal to zero) may be rejected, if the current value of test χ^2 at the end of the observation time window (N values) is bigger than the critical value (χ^2_{max}) for the selected level α of significance. If the zero hypothesis is rejected, the correction of the set point SP_{corr} of

PI controller occurs automatically (Fig. 6). The correction takes place only once if it is necessary to complete the successive time window of the width of N of the probes. If the correction does not render the required results during the time of the next time window, another correction occurs at the end.

In Fig. 6 the mathematical and logical relations of the statistical correction module are explained in detail, to reproduce an example of this module. Algorithm of the drift error correction module can by described in the following steps:

- Take measurements of specified time
- Calculate the sum *S*
- At the end of the specified time (time window) Calculate χ^2 according eq. 14.
- Compare values χ^2 and χ^2_{max}
- If χ^2 is greater than χ^2_{max} correct set point of PI controller, if not keep previous value.

The correction module parameters:
N – sample size, for the case T_p=1[s] it is the width of the time window, in the course of which observation takes place (time scope of the observation of the correction module),
Corr –value by which the set point may be altered at the end of each observation time scope
χ^2_{max} – value dependent on the selected level α of significance.

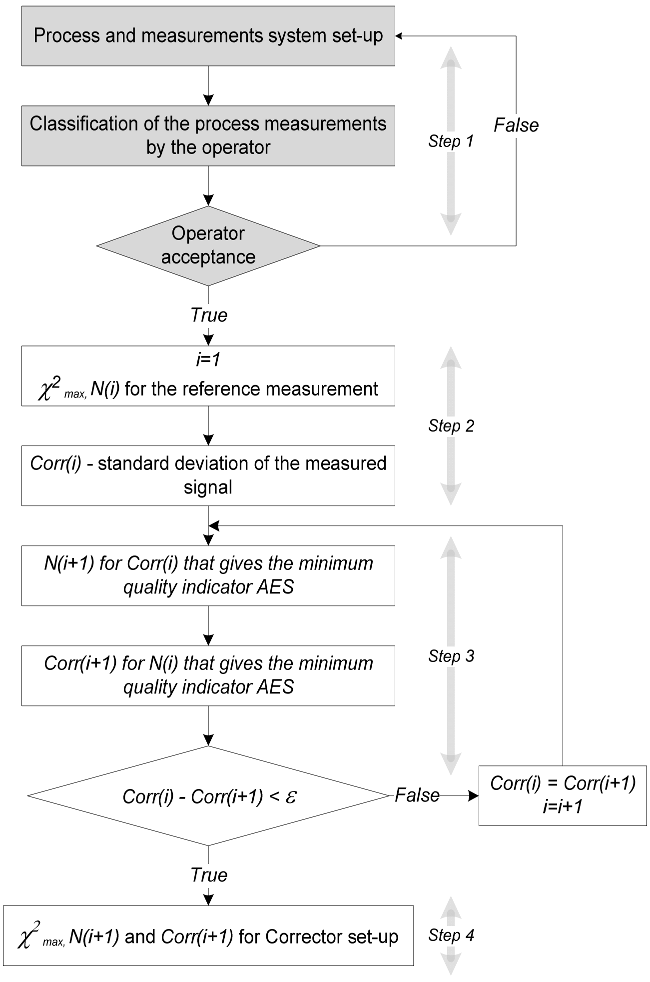


Figure 7. Iterative algorithm of *Corr, N,* χ^2_{max} parameters estimation.

To secure proper functioning of the correction module, three parameters should be determined: $\chi^2_{max,}$ *N* and *Corr* in a iterative manner explicated in Fig. 7. Values necessary for correction module can also be estimated in an other way discussed bellow. The value of χ^2_{max} is derived from the expert knowledge of the operator, who knows what instances of the system behaviour are allowable.

The numerical value of χ^2_{max} is derived from the operator's assessment of a selected interval of the system performance regarded as reference time. At the same time, it is assumed that there are such values of *N* and *Corr* that minimize AES performance index in the control system. The value of *Corr* is responsible for the excitation of the control system. The insignificantly low value may not be detected by the control system; whereas, too high value of *Corr* may lead to unnecessary shift of the set point, and, in consequence, worsened quality of the process control. The value of *N* should be selected in a manner enabling the sample to be representative from the point of view of the statistical properties of the selected test. However, if the value of *N* is big, the time of waiting for the results is too long in relation to the rate of the changes taking place during the process.

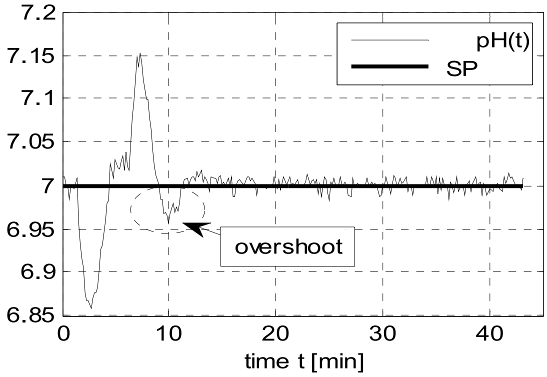
The values of *N* and *Corr* were designated in an experimental manner in the next part of the paper (Table. 1), in accordance with the methodology of the selection of the initial value of *N* that considers the average time of the duration of the shortest disturbance to which the correction module should react. The initial value of *Corr* was set at the level comparable with the value of the measurement noises, as the correction module shall support the removal of long-term effects of the disturbances, not just their temporary impacts. Iterative algorithm of parameters estimation (*Corr, N,* χ^2_{max}) for the drift error correction module can by described in following steps:

- Step 1. System set-up, where expert knowledge is needed. Operator has to point out time period of the process operation that is acceptable for him.
- Step 2. Based on the selected period of the process operation initial values for drift error correction module parameters can be found.
- Step 3. Starting form initial values during regular operation of process parameters of *Corr* and *N* are estimated to find minimum of specified performance index.
- Step 4. Process operation with fixed module parameters.

VI. Experimental Results

The controller may be adjusted for different degrees of control aggressiveness, to meet the technical requirements. Although many new tuning methods for PID controller were proposed , in industrial practice the few most popular are used. Due to the presence of the dead time, authors have chosen two popular tuning methods for the PI controller: Ziegler-Nichols method (Z-N) [29] and Chien-Hornes-Reswick method [30] in the conservative (C-H-Rc) form. It is assumed that system can work appropriately under conservative tuning, enabling economical service. To achieve such requirement the authors applied Chien-Hornes-Reswick method [30] assuming fast, yet aperiodic reaching the set point. Obtained tuning parameters of controller are as follows: K_c=2.8 and integration time

T_i=0.55[min]. As an alternative an aggressively tuned controller (K_c=5.4, Tc=0.32[min]) can be proposed. Performance for different tuning of controllers were compared for the same large disturbance that changed incoming flow of acid form 0.35 to 0.5 [l/min] for 5 minutes and than flow resumes to initial value (0.35).



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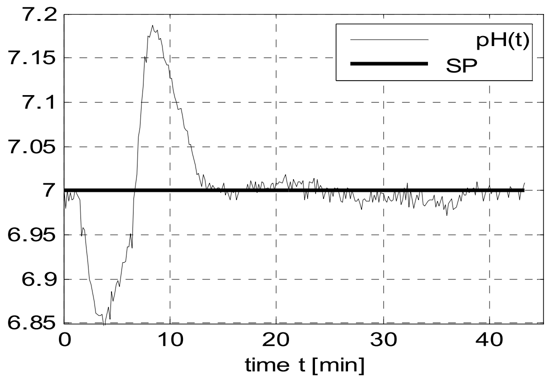
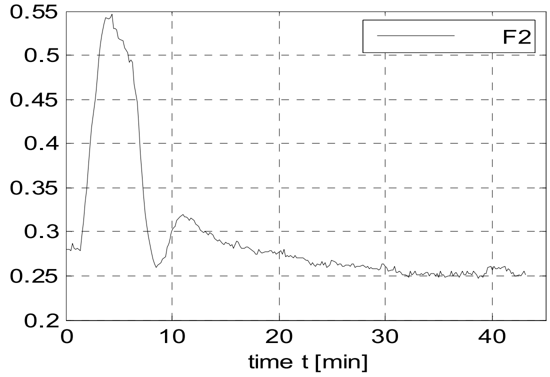


b)

Figure 8. a) Graph of pH aggressive controller for large disturbances, b) Graph of pH conservative controller for large disturbances.

The aggressively tuned controller (fig. 8a) operates with shorter settling time and lower error performance index, but has overshoot in comparison to the conservatively tuned controller (fig. 8b). However the aggressively tuned controller operates well in terms of control error it can be not accepted because of aggressive change of control signal (Fig. 9a). Controller output shown in Fig. 9b is much more acceptable for process operator. The authors have an attempt at improving the control quality without the necessity of increasing the aggressiveness of tunings. The objective of further experiments is to find needed parameters (*N, Corr,* χ^2_{max}) for correction module. Set-ups for this experiments were conducted in time cycles of the length of 1 hour (Fig. 10). At the beginning of the cycle, strong disturbance in the form of step response of the process flow was evoked (the nominal value 0.35 [l/min]). At zero time, the value of the process flow was increased up to 0.5 [l/min], and after 5 minutes the flow resumed its nominal value. The following 55 minutes of the experiment ran without any enforced disturbances. After one hour the experiment was repeated with other parameters of the corrector. The disturbances illustrated in part 2 of the Figure 10 (40 [min]) after stabilization time designated as part 1(20 [min]) (Fig. 10) were, in reality, the main subject of interest. Initially, strong disturbance of the flow (part 1, 20[min]) was, first and foremost, a kind of a separator between the successive experiments.



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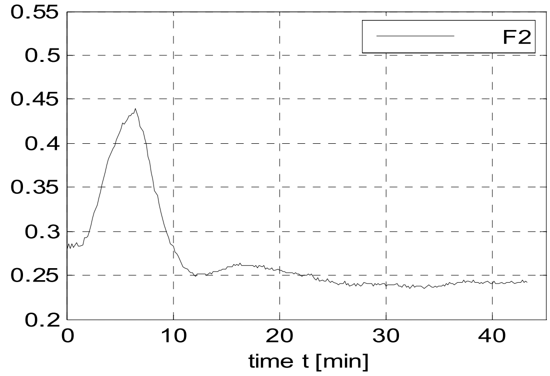

b)

Figure 9. a) Graph of controller output for aggressive tuning, b) Graph of controller output for conservative tuning.

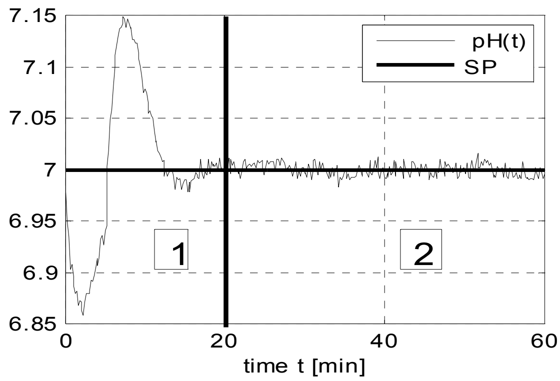

Figure 10. Graph of pH and the corrected set point.

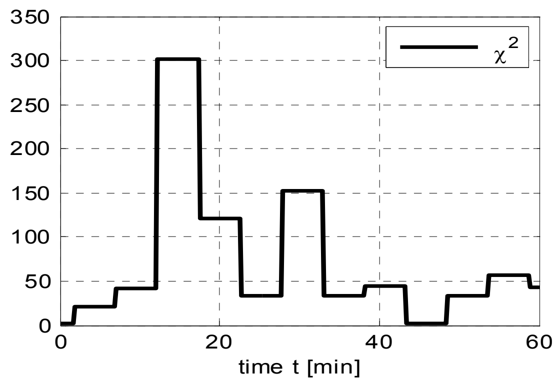

Figure 11. Graph of χ^2 during the experiment.

Due to the emergence of the disturbance in the system (Fig. 10. part 1) the value of test χ^2 is significantly increased, but because of the controller it is minimized as the impact of the disturbance fades away (Fig. 11).

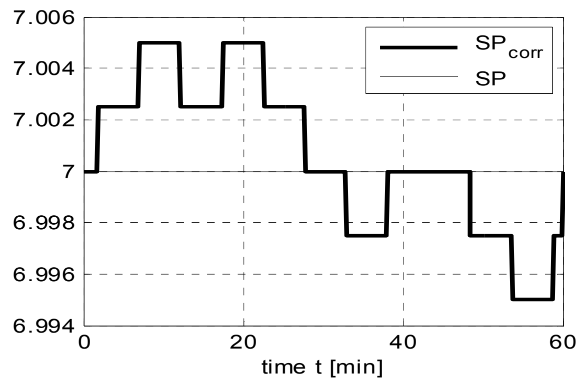

Figure 12. Graph of the corrected set point (SP_{corr}) and the set point (SP) during the experiment.

To determine the initial values of the corrector module the adjustment time qualified by the operator as the reference performance may be selected. On the basis of the selected time, a histogram of the times of the process value below and above the set point may be assumed, as well as typical process performance, which may be treated as a model and reference point for further assessment of other fragments of the course of the process. On such grounds, value N=310 [s] was designated to facilitate the observation of all important phenomena of the process for the level of relevance α=0.1. Thus, the value χ^2_{max} =2.7 is derived. The values of the test indicated in Fig. 11 significantly diverge from the assumed value of χ^2_{max}. However, the experiments proved that it is possible to maintain the values of χ^2 <2.7 in the steady state with the probability corresponding to the confidence level of α. Likewise, as χ^2_{max} value was derived, the correction value should be designated, to modify the set point in the case of detecting any deviation tendencies in the control. Such value should be low and comparable with the amplitude of the measurement noise; hence, the initial value was assumed as 0.0025pH. For such assumed values, the set point may be corrected by the correction module for many times in the course of a one hour experiment, as shown in the Figure (Fig. 12).

The corrected set point oscillates around the accurate set point not exceeding 0.005pH. It may seem that such insignificant changes in the values may not exert an impact on the system performance; however, further results indicate to the existence of such impact and its measurability. The tuning parameters of the correction module were assumed partially arbitrarily; therefore, there is always a question to be addressed if it is possible to find better parameters. As one of the criteria of searching the optimal values, the minimization of the quality ratio of the process control for the working correction module may be assumed. It is also important to take into account the control effort especially when the actuator includes an electric motor. Finally the quality ratio (performance index) of the process control was defined as (eq. 15 and 16):

$$AES = \frac{\sum_{i=1}^{k}\left(\left|PV_i - SP\right|\right)}{k} \tag{15}$$

$$AS\Delta u = \frac{\sum_{i=1}^{k}\left(\left|u_i - u_{i-1}\right|\right)}{k} \tag{16}$$

where:
k-denotes the number of samples collected for the calculations (k=3600).

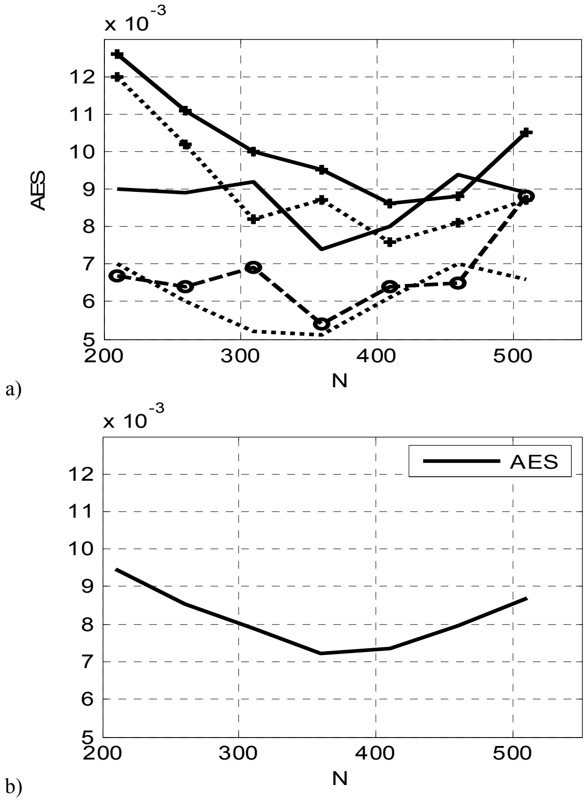

Figure 13. Dependence of the process control quality ratio on the width (*N*) of time window, a-experimental results, b-average value (time of the experiments: 48 h).

Initial results of the conducted simulations, although not discussed in the paper, indicate to the existence of a minimal value of such ratio. In the face of the complexity of the process phenomena, in practice, simulation tests cannot provide accurate information on the values of the parameters, but only make the existence of the minimum seem to be more probable. To search the minimum, series of experiments were carried out on a real object, with the time scope of 1 hour for variable values of *N* and *Corr* in accordance with the same scheme as the one for the first experiment described above (Fig. 13a). The derived graphs of the quality ratio of the control, depending on the width *N* of the time window illustrate that there is a minimum for *N*=360 [s] (Fig.13b). The experiments were repeated for many times for the value of *Corr* within the range of <0 ,0.06>. All the experiments led to the conclusion on the existence of the minimum, yet, its value strongly depends on parameter *Corr*. For *Corr*=0.0075 the lowest value of the process performance index was derived.

So far, investigations of the impact of *Corr* have been repeated for many times, the mean results of which are shown on the graph (Fig 14). The majority of the characteristics are rather flat within the investigated range. Two local minimum values are visible on some parts of the graph, but none of the characteristics does not show the minimum for *Corr*=0. This proves a positive impact of the correction module on the general performance of the control system. Likewise, all the conducted experiments confirm the existence of the minimum of the quality ratio of the system performance for the changes in parameter *Corr*. The mean results (Fig. 14) explicitly indicate, at the same time, the minimum for the value of *Corr* within the range of 0.005-0.0075.

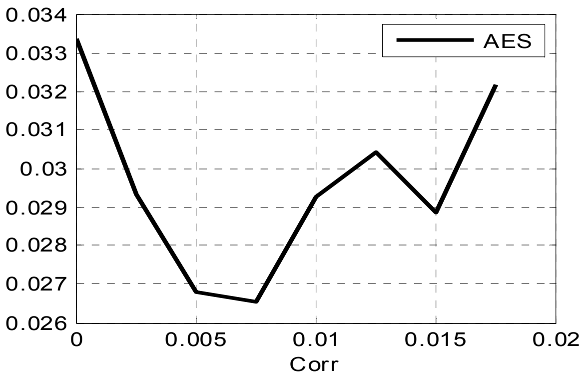

Figure 14. Dependence of the quality ratio of the process control on the value of the correction of *Corr* (the time of the experiments: 64 h).

The derived value of the parameters of the correction module was compiled in Table 1. The parameters are characterized by a certain tolerance due to their averaging and should be verified in practice. Accordingly, a series of experiments was performed to compare the operation of the controller equipped with the correction module and without it.

Parameter	χ^2_{max}	*Corr*	*N*
Value	2.7	0.005÷0.0075	310÷360

Tab.1. Optimal values of the correction module for the pilot neutralization installation.

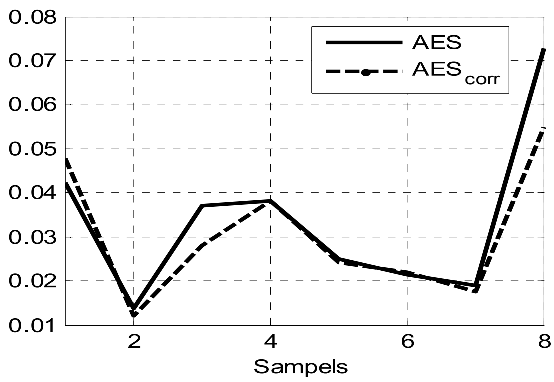

Figure 15. Comparison of the quality of control in the successive experiments (time of the experiments: 32h).

The experiments involved multiple repetitions of the tests with the graphs analogical to the one plotted in Fig.8, for the controllers with the correction module and without the module, alternately. Each point (sample) shown in graphs 15 and 16 is an average of several tests conducted one by one. Eight series of such tests were conducted for the sake of the comparison. Due to *AES* performance index (Fig. 15), the controller equipped with the correction module performed better in five cases, in two cases – on the same level of quality and, in one case- worse than the controller without the correction module. In consideration of the control costs index $AS\Delta u$ (Fig. 16), in each case the controller with the correction module performer better. Effort to control is smaller. This means lower operating frequency of electrical actuator.

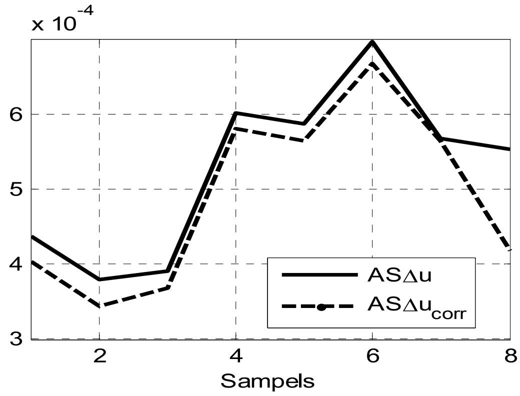

Figure 16. Comparison between the control tuning (time of the experiments: 32h).

To assess the performance of the correction module on the grounds of *AES* and $AS\Delta u$ calculations of the weighted quality control ratio were made in consideration of the deviation of control and control costs:

$$AES_{norm}(i) = \frac{AES(i)}{\max\left(AES, AES_{corr}\right)} \tag{17}$$

$$AS\Delta u_{norm}(i) = \frac{AS\Delta u(i)}{\max\left(AS\Delta u, AS\Delta u_{corr}\right)} \tag{18}$$

$$WAES = 0.5 \cdot AES_{norm} + 0.5 \cdot AS\Delta u_{norm} \tag{19}$$

Analogically to *WAES* (eq. 17-19), *WAEScorr* ratio is calculated in the next step. The ratios were illustrated in Fig. 17. For the applied weight of 0.5 the controller with the correction module performed better in seven cases, and worse only in one case.

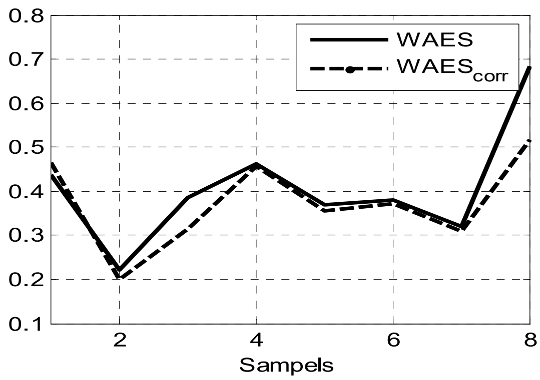

Figure 17. Comparison of the weighted control quality ratios (time of the experiments: 32h).

Thus, the calculated ratio also makes it possible to compare the controllers with different degree of aggressiveness of tunings and to render the information whether the decrease in the deviation is proportional to the increase in the control cost. To enable a more in-depth comparison, experiments analogical to the one presented in Fig. 10. were conducted with the controller tuned aggressively (K_c=5.4, Tc=0.32[min]) and conservatively. The controller tuned conservatively is almost twice less aggressive, and its integral constant is twice bigger (Kc=2.8, Tc=0.55[min]).

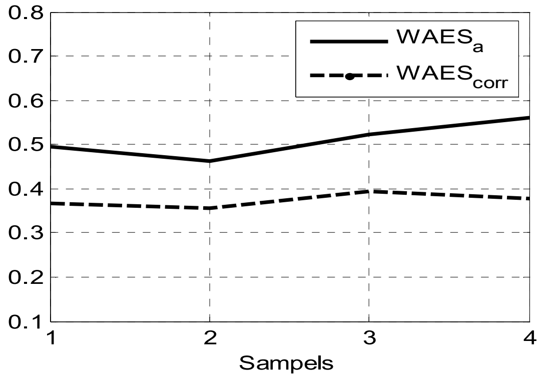

Figure 18. Comparison of the aggressive and conservative tuning.

The tests were run in a series, alternately for the aggressive controller and the conservative one to eliminate possible external impacts. *AES* performance index for the controller tuned aggressively is lower than the corresponding *AES* for the system with the controller tuned conservatively, but the costs involved in the control and expressed by $AS\Delta u$ ratio is significantly higher. To compare both systems, the weighted ratio proposed above was used. The values derived for both systems (*WAESa* for the system aggressively tuned and *AEScorr* for conservatively tuned with the correction module) were indicated in Fig. 18. In all of the four cases the weighed ratio was lower for the system conservatively tuned and equipped with the correction module. In the systems where only the minimization of the deviation index (*AES*) is essentials, aggressive control is preferred and in all of the four cases settling time is better (Fig. 19).

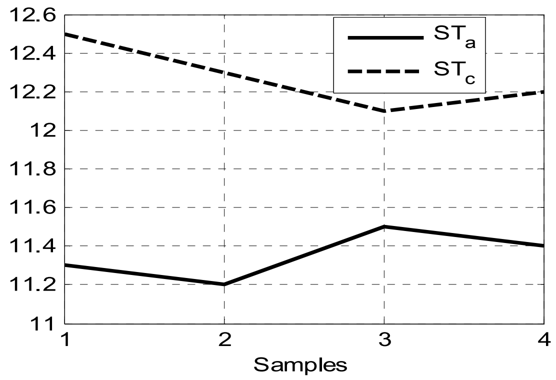

Figure 19. Comparison of the aggressive and conservative tuning- settling time.

In the case of conservative tuning there is no overshoot or it is very small as it was for sample number 2 (Fig. 20). For this system small overshoot can be accepted because time constant for the change in process is the same in both directions but it is not the case in general. Tuning procedure is chosen accordingly to the desired closed loop performance as a trade of expected *AES* performance index and economical aspect expressed by $AS\Delta u$ ratio.

However, in many cases, if the costs of control are important, conservative control is more appropriate because of economical aspects. As indicated in Fig. 17, in most of the cases the application of the correction model improves the performance of the conservatively tuned controller, which provides a sufficient assumption for its use in control systems. Improvement is done not by permanent aggressive controller operation but temporary action when steady state offset is detected form statistical point of view. When process operates well in comparison to operation in time period pointed out by operator, the corrector module does not react and the controller works in conservative way as it is expected. The phenomena that obstruct control in the neutralization process may also be observed in other systems. This concept was verified for the control of the aeration process in a bio-technological reactor [31]. The simplicity of the correction algorithm, which does not require big calculation load, enables its application for various hardware and software platforms. Accordingly, the correction module may also be used in many other control systems.

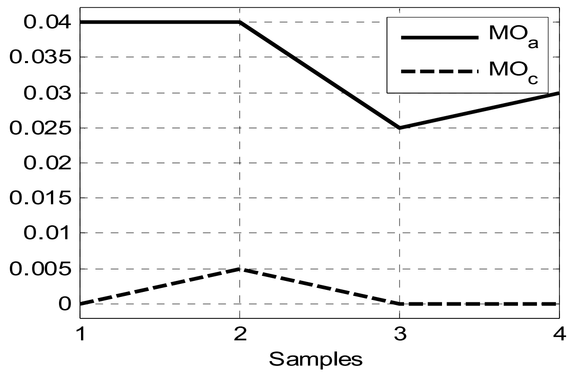

Figure 20. Comparison of the aggressive and conservative tuning-maximum overshoot.

An example of an implementation of the correction module in the ladder diagram is presented in Fig. 21. It is a practical implementation of drift error correction module algorithm described on Fig 6. In the illustrated case, the module performs in periodic task every with the assumed sampling time 1[s]. Generally, the corrector module can be implemented in the controller in any way to ensure its periodic operation, which constant sampling period. Practical implementation of the correction module was done on Allen-Bradley controller because it fit to most demanding application needs. The Allen-Bradley PLC offer modular architectures and a range of I/O and network options and deliver world-class capabilities for process control. This is suitable for distributed or supervisory control applications, and provides good reliability and performance. It have to be stressed that the algorithm consists of simple mathematical functions and thus may be run on any programmable PLC in any programming language.

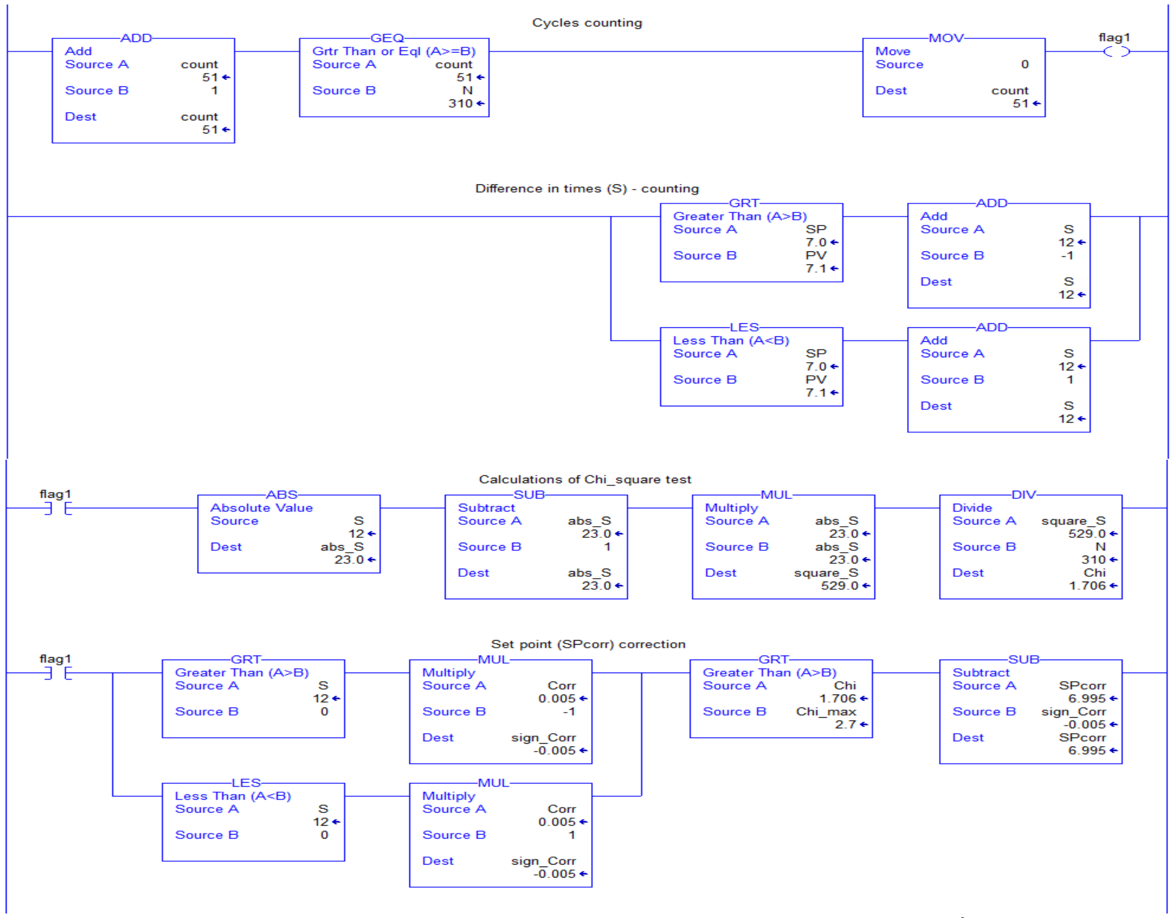

Figure. 21. Practical implementation of the correction module into Allen-Bradley controller for N=310, $Corr$=0.005 and χ^2_{max} =2.7

VII. Conclusion

The paper focused on practical possibilities of determining a minimal value of the quality ratio of the process by means of well-recognized statistical tools. The discussed algorithm was successfully implemented in the pilot neutralization process. Experimentally optimal parameters of the corrector algorithm were designated. It may be concluded that control systems aggressively adjusted cannot improve their performance due to the performance of the corrector module. However, for aggressively adjusted systems the costs of control may increase disproportionally in relation to the improvement of the quality control. The impact of the corrector shall be bigger, if the controller is adjusted conservatively. Conservative adjustment of the controller is commonly used industrial practice to protect the actuators. An obvious and decisive advantage of the proposed methodology is no requirement of introducing additional disturbances into the process. The control errors are analyzed and, in necessary circumstances, attempts at automatic correction of the set point made, as opposed to alternative methods of using the corrector just to modify the tuning parameters of the controller. The performance of the system is by no means limited to correction measures, but may also serve to signal failures in the case of exceeding the assumed error values. The neutralization process is not the only one that exhibits such difficulties in control, hence, the proposed approach has a generic aspect and is applicable far beyond a narrow area of neutralization processes. The presented algorithm may easily be implemented by engineers in any programmable controllers reducing control effort in system.

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