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ON MODIFICATION OF A PID ALGORITHM FOR DECREASING OF WIND-UP EFFECT

A paper presents an approach for reduction of anti-windup effects induced by constraints of actuator action in closed-loop control systems with PID Algorithm. A discussion of different, common used approaches, for reduction of this effect is presented at first. An idea of dynamic modification of reference input, not inducing saturation at actuator in closed-loop is derived. The proposed modification can be used in case of amplitude and velocity limitation as well. The modification will not induce any dynamic into closed-loop and will not alter stability properties of the entire control system. Simulation results, comparing efficiency of mentioned techniques and the proposed method would be presented and discussed on example of two SISO linear systems.

MODYFIKACJA ALGORYTMU REGULATORA PID DLA ZMNIEJSZENIA ZJAWISKA WIND-UP

W pracy zaprezentowano modyfikację algorytmu cyfrowego regulatora PID, której celem jest ograniczenie negatywnego wpływu ograniczeń wprowadzanych przez element wykonawczy na przebiegi regulacji. Modyfikacja polega na dynamicznym kształtowaniu przebiegu wartości zadanej w taki sposób, by w zespole wykonawczym nie występowało przekraczanie dopuszczalnych ograniczeń. Wprowadzona modyfikacja nie zmienia właściwości dynamicznych w zakresie liniowej pracy układu zamkniętego, a zatem nie zmienia parametrów stabilności układu. Zmodyfikowany algorytm został porównany ze stosowanymi formami algorytmu PID na przykładzie 2 modeli układów liniowych drugiego rzędu z opóźnieniami.

1. INTRODUCTION

The most popular and used in industrial applications, PID control algorithm yields some effects involved by limitations always existing in real systems: lower and upper limits of actuator output and limited speed of actuator action. These constraints induce a non-linear action in closed-loop control system. Reaction of actuator can't follow the controller output and in effect it destroys possible efficiency of PID algorithm.
It can be observed, e.g. at sudden change of reference value, when actuator can't repeat reaction of the differential term. This case will usually yield a delayed answer of the closed-loop system. Other, more disturbing case will appear, when discrepancies between controller output and actuator output, cumulated by memory of integrating part of controller, will involve a wind-up effect. This can induce an exceeded and prolonged action of integrating term and can completely destroy expected reaction of PID algorithm. Both effects were observed a long time ago and were hard to cope in times of

electronic control devices. Hence different modifications of standard algorithms were proposed; modified action of differential term by introduction of inertia or excluding a reference value signal variation from input of differential (or even proportional) term. Both approaches are still used, but in fact they decrease possible efficiency of PID control algorithm. The mentioned effects of PID control appear only in disadvantageous conditions: significant variation of set value, actuator output close to boundary position or in case sudden disturbance. At the first two cases a process operator can manage by introduction slow variations of reference value and with at the last he can try to cope with a proper compensation of disturbing quantities.

Digital processors, introduced in control system devices, have created new possibilities. Robust solutions, repeating of mentioned approaches – limitation of differential action and introduction conditional integration (CI) within I term are still used [2,6,9]. More sophisticated algorithmic approaches like anti-wind up compensation [3,4,5,8,10,11], time variable modification of reference value signal or back-calculation methods are proposed but they demand more calculation effort. The proposed approach is based on simple modifications and standard digital PID algorithm, which can be expressed in form of a few additional operations within controller action. It can be used in existing PC-controllers or even soft control systems by small modification of basic code.

2. INVESTIGATED SYSTEM AND PID ALGORITHMS

The presented approach can be used for digital control systems, where all signals are recorded with the same sampling interval Δ. An instant value of each investigated signal v, at time $\tau = t\,\Delta$, will be marked as $v_t = v(\tau)$. Let consider a discrete-time model of plant

$$A(q^{-1})y_t = B(q^{-1})q^{-d}u_t \tag{1}$$

where y_t is the plant output, u_t is the controlled input, $d \geq 1$ is the plant delay. Polynomials $A(q^{-1})$ and $B(q^{-1})$, determined by a shift operator q^{-1} $(q^{-p}v_k = v_{k-p})$

$$\begin{aligned} A(q^{-1}) &= 1 + a_1 q^{-1} + \ldots + a_{nA} q^{-nA} \\ B(q^{-1}) &= 1 + b_1 q^{-1} + \ldots + b_{nB} q^{-nB} \end{aligned} \tag{2}$$

are relatively proper and of real coefficients. The constraints of the actuator part of the control system are represented by area of permissible magnitudes

$$U_M = \langle u_{low}, u_{high} \rangle \tag{3}$$

valve position and a range of possible changes within one sampling interval is bounded

$$U_V = \{u_t : |u_t - u_{t-1}| < V * (u_{high} - u_{low}) \cap u_t \in U_M \cap u_{t-1} \in U_M\} \tag{4}$$

where V is the greatest possible actuator velocity.

It is obvious that in real applications both constraints exist. A design of a control system shall always yield a surplus of actuator output as to drive plant output into area of high values without problems, but its relative value is not very high (usually 50-100% of nominal high position) as to not oversize entire installation. Fast reaction onto disturbance impact demands small sampling interval of the control system and therefore actuator can alter its output only a fraction V (usually 5-20%) of maximal displacement within one sampling interval.

Output signal v_t of the ideal digital PID algorithm (I-PID) reflects three forms of processing the control error e_t: term proportional to e_t, derivative of e_t for fast compensation of disturbances and integral term for asymptotic removal of error e_t

$$\begin{aligned} &v_t = G_{I\text{-}PID}(q^{-1})e_t, \qquad e_t = w_t - y_t \\ &G_{I\text{-}PID}(q^{-1}) = k_P + k_I\frac{(1+q^{-1})}{1-q^{-1}} + k_D(1-q^{-1}) = K[1+\frac{\Delta(1+q^{-1})}{2T_I(1-q^{-1})} + \frac{T_D}{\Delta}(1-q^{-1})] \end{aligned} \tag{5}$$

Above linear relation between control error e_t and control v_t reflects an ideal difference operation, that at short sampling interval can't be properly processed by control system - a factor T_D/Δ will demand high and fast actuator reactions. A "real" differentiation is widely used in form discrete-time difference filtered by first order inertia T_V [6,9]

$$G_{R\text{-}PID}(q^{-1}) = \frac{p_0 + p_1q^{-1} + p_2q^{-2}}{(1-q^{-1})(1-c_1q^{-1})} = \frac{P(q^{-1})}{M(q^{-1})}, \qquad p_0 = \frac{K}{1+T_V/\Delta}\left[1 + \frac{T_D+T_V}{\Delta} + \frac{\Delta+T_V}{2T_I}\right] \tag{6}$$

$$p_1 = \frac{K}{1+T_V/\Delta}\left[-1+\frac{\Delta}{2T_I} - 2\frac{(T_D+T_V)}{\Delta}\right], \qquad p_2 = \frac{K}{1+T_V/\Delta}\left[\frac{T_D+T_V}{\Delta} - \frac{T_V}{2T_I}\right], \qquad c_1 = \frac{T_V}{T_V+\Delta}$$

It has practical motivation - a filtered derivation in (6) has limited value at instant t of change of w_t and impact of derivative action is prolonged by inertia T_V.

Industrial solutions [1,7] prefer a distinct presentation of different controller actions, see. Fig. 1. This form is more suitable for separate tuning of controller actions, however needs more dynamic blocks. Algorithm, with separate PID actions, will be called at testing as R-PID. This form has other advantage: controller actions u_p, u_d or u_i, (Fig.1) can be calculated and modified separately, e.g. introduction of set value into P-term (dashed line). In this form is very easy to introduce schemes for bump-less action or limitation of saturation in I-term [1,4,6,7].

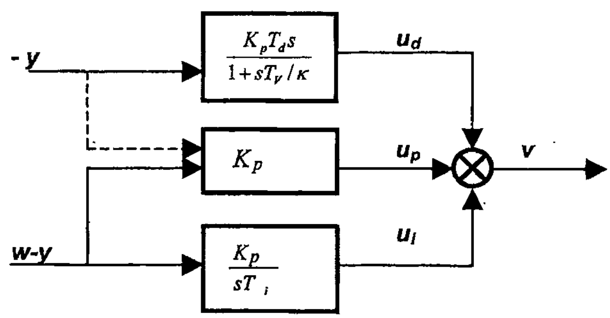

Fig.1. Common used structure of industrial applied PID algorithm

In theoretical investigations is used a generalised form of controller transfer function

$$M(q^{-1})v_t = R(q^{-1})w_t - P(q^{-1})y_t \tag{7}$$

where $M(q^{-1})$, $R(q^{-1})$ and $P(q^{-1})$ are polynomials of operator q^{-1} [4,5]. The introduction of inertia in differential term (6) in a basic algorithm (5) will increase an order of polynomial $M(q^{-1})$ and introduce a parameter – c_1, that can be used for optimisation of control-

ler dynamics (except parameters K, T_I, T_D). A polynomial $R(q^{-1})$ is defined as $\rho P(q^{-1})$ with $0<\rho<1$. This form of controller will be called at testing TF-PID.
The general form (7) can incorporate other algorithms and is suitable for investigations dynamic properties of closed-loop systems [6,10,11]. This tool, for decreasing windup effects, is induced by numerous techniques:

C 1. Output of integral term u_I is limited to a determined value $V1$,

C 2. Integration action u_I is halted on constant level, when the control error is large, i.e. is $|e_t/e_{max}| > E1 > 0$, (where e_{max} is maximal value of error)

C 3. Integration action u_I is halted, when the controller output saturates the actuator possibilities, i.e. $v_t \notin U_V$ (4),

C 4. the integration action u_I is halted when the controller output saturates the actuator possibilities, i.e. $v_t \notin U_V$ (4) and product $v_t G_0 > 0$, (G_0 is a static gain of plant).

Efficiency of CI technique, based on conditions C1 – C4, is dependent on dynamic properties of controlled plant. The last two approaches are more flexible and are active only when saturation in actuator will appear. The conditions C1, C2 need to perform some tests, for fitting parameters V_1, E_1. At working controller, they are not adapting to variable plant conditions. The approaches (C1 ÷ C4) differ only in conditions, when they are activated, but they are based on the same idea – to stop the integration of control error for some time interval. An approach, based on more active attitude to the problem was presented in [12], where a technique of so called "back-calculation" (BC-PID) was proposed. This approach is based on idea, presented by Fig. 2.

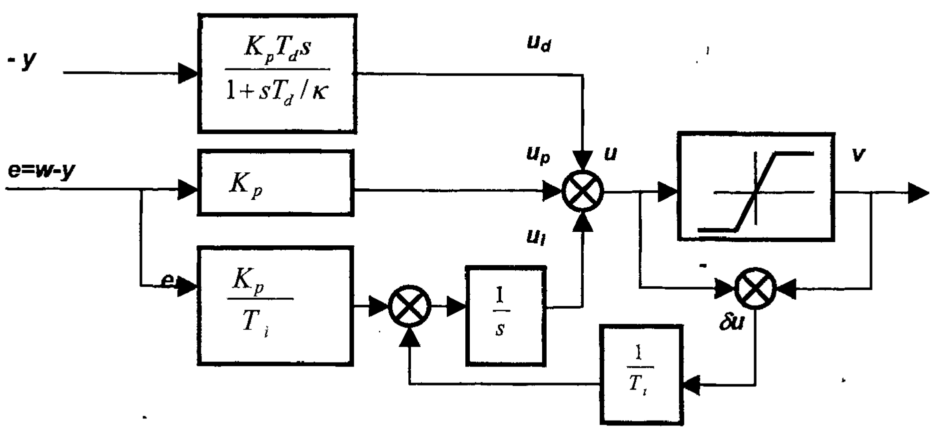

Fig. 2. Structure of control algorithm with back-up calculation

The input value into integral part in controller

$$e_I = \frac{K_P}{T_I} e + \frac{1}{T_t}(v - u) \tag{8}$$

is reduced in case of limitation in actuator output, represented as saturation on Fig. 2. In this approach no CI-conditions are necessary. The integral action is performed without change, when saturation area in actuator is not attained. A designer has to choice a constant T_t for better fitting PID controller to the system properties.

3. DYNAMIC MODIFICATION OF A PID ALGORITHM FOR DECREASIG OF WIND-UP EFFECT

All presented modifications of basic PID algorithm have one aim; to deal with to big error value in a closed loop. This value, processed by controller can't be realised by the actuator. All mentioned modifications are "fixed" in a sense, that its action does not dependent on actual possibilities of controller-actuator set. Splitting an interval of differential action, by introduction of inertia T_V (6) or direct reduction of its impact (7) is always active, irrespective of magnitude of w_t-y_t. However at small step changes of w_t, the basic action (5) of PID can be realised. Conditions C1 – C2 have introduced constraints on integral action without any test of actual actuator position. Conditions C3 – C4 are activated when necessary. The idea of back calculation is better, it yields active counter-measure to windup effect. In case of limitation of actuator signal, the integral term has been fed with input e_I of opposite sign to actual control error and in effect the memory of integral term was decreased but its action can be not suitable at disturbances.

The idea of proposed approach is: to introduce, into controller action, a modification of actual reference value w_t to value r_t, that is always acceptable by controller and actuator. Then controller output, calculated from corresponding relation of PID controller and determined by settings - K, T_I, T_D, will always hold conditions (3) and (4). The corresponding conditions can be derived from basic algorithm of PID (5) or (6).

Let consider a compact form of PID controller equation derived from (6)

$$v_t M(q^{-1}) = e_t P(q^{-1}). \tag{9}$$

The basic form of controller (6) (with c_I=0) combines an error e_t at discrete-time t with controller parameters p_0, p_1 and p_2

$$e_t = r_t - y_t = (v_t - v_{t-1} - p_1 e_{t-1} - p_2 e_{t-2}) / p_0 . \tag{10}$$

A change of controller output is then determined by

$$\Delta v_t = v_t - v_{t-1} = p_0 e_t + p_1 e_{t-1} + p_2 e_{t-2} . \tag{11}$$

At time instant t, a maximal positive change of controller output (that can be realised by actuator) Δv_+ is limited, either by saturation of actuator or velocity of its displacement

$$\Delta v_+ = \min(u_{high} - v_{t-1}, V * \Delta) \tag{12}$$

and respectively maximal negative change Δv_- is equal

$$\Delta v_- = \max(u_{low} - v_{t-1}, -V * \Delta) \tag{13}$$

where V is maximal velocity of actuator displacement (4). The controller output will not excess actuator constraints, when at any discrete time t, the output v_t will contain within interval <Δv₋, Δv₊>. Hence a simple modification of the control error e_t can be proposed

$$e_t = \begin{cases} w_t - y_t & \Leftrightarrow v_t \in \langle \Delta v_- + v_{t-1}, \Delta v_+ + v_{t-1} \rangle \\ r_t - y_t & \Leftrightarrow v_t < \Delta v_- + v_{t-1} \quad \& \quad r_t = y_t + [\Delta v_- - e_{t-1} p_1 - e_{t-2} p_2] / p_0 \\ r_t - y_t & \Leftrightarrow v_t > \Delta v_+ + v_{t-1} \quad \& \quad r_t = y_t + [\Delta v_+ - e_{t-1} p_1 - e_{t-2} p_2] / p_0 \end{cases} \tag{14}$$

While the controller output v_t is inside the range of accessible actuator output, the reference value is not changed and controller action is consistent with basic algorithm (5). If the controller output will exceed the acceptable area (4), new virtual reference value r_t will appear, that will induce new control error e_t, small enough to satisfy present constraints of controller output variation (12), (13).

This modification can be used for any PID controller algorithm, e.g. (5) ÷ (8), but the most attractive case is (5). The controller algorithm will preserve an efficiency of powerful action of derivative term in case of disturbance compensation and will "dose" changes of reference value as big as possible (14). It should be observed, that magnitudes of accessible output variation Δv_- and Δv_+ are dependent on previous position of actuator v_{t-1} and will always use the entire actuator output. They are dynamic fitted to actuator position, what justify its name Dynamic Modification of reference value PID algorithm (DM-PID). The actuator output (4) will never exceed its constraints. This modification does not demand any fitting, as in case of the other algorithm (6) – (8). This algorithm will not induce mentioned reduction of integral action, observed at back-calculation scheme. It will not demand any additional optimisation of T_t and can be used in adaptive control systems.

4. TESTING OF PID ALGORITHMS

In this section some results of testing are presented, for comparison of efficiency of approaches, presented in Section 2, in case of actuator constraints and different operation conditions of closed-loop control system. A testing was performed on example of 2 linear, dynamic system of third order with delays. As a basic controller, the optimal parameters (K, T_I, T_D) for I-PID (5) algorithm, operating without any constraints were determined. The settings K, T_I, T_D were next used in all compared algorithms, with optimisation of additional parameter (or parameters), characteristic for considered modification of basic algorithm.

The constraints of actuator were introduced on its output (e.g. maximal valve flow) and velocity of its changes (e.g. maximal velocity of valve displacement). The output constraints were equivalent to: minimal value equal zero and maximal value corresponding to appr. 150 % of greatest considered system output at steady state. The velocity limitation was set to 10% of the total actuator range of output, at each sampling interval.

4.1. Controlled Processes

As the first was investigated an inertial process, with variable delay, that can be represented by a transfer function of the form

$$P1(s) = \frac{e^{-sT_d}}{1+sT_3}\left(\frac{K_1}{1+sT_1} + \frac{K_2}{1+sT_2}\right) \quad . \quad (15)$$

$$K_1 = 3, \quad T_1 = 4s, \quad K_2 = 6, \quad T_2 = 20s, \quad T_3 = 10s, \quad T_d = 5\text{s}, 11\text{s}$$

Variable number of T_d in this model has to model different process dynamics; medium and large delay process with conservative controller settings. The sampling interval was equal Δ=1s. In the following tables, results will be marked as P1_5 and P1_11.

The second example was a non-minimal phase process represented by transfer function of the form

$$P2(s) = \frac{e^{-sT_d}}{1+sT_3}\left(\frac{K_1}{1+sT_1} - \frac{K_2}{1+sT_2}\right) \tag{16}$$

$$K_1 = 50, \quad T_1 = 10s, \quad K_2 = 30, \quad T_2 = 4s, \quad T_3 = 20s, \quad T_d = 4s$$

The non-minimal phase processes are difficult to control, hence results observed at this process can be interesting and convincing.

4.2. Simulation conditions and performance indices

Testing of controller algorithms and their efficiency was performed in structure presented on Fig. 3. The controller has to cope with variable reference value w_t or with impact of disturbance d_t acting on the output of plant via a low-pass filter.

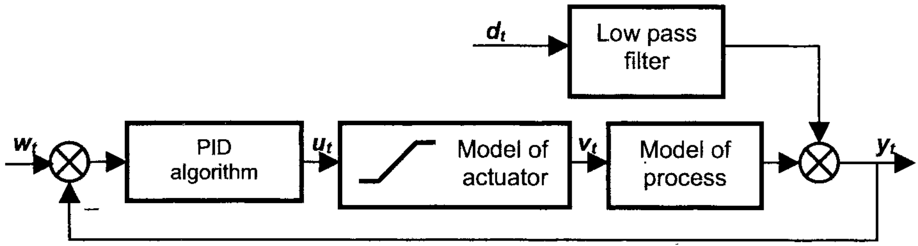

Fig.3. Structure of closed-loop system modelling for comparison of PID-algorithms

Testing of all considered algorithms has consisted of two parts. First was tested a control in case of variable reference input value, (disturbance d_t= 0). This test had to emulate real like conditions and therefore system responses for different magnitude and actuator working conditions were simulated. The test has a form shown on Fig.4a,

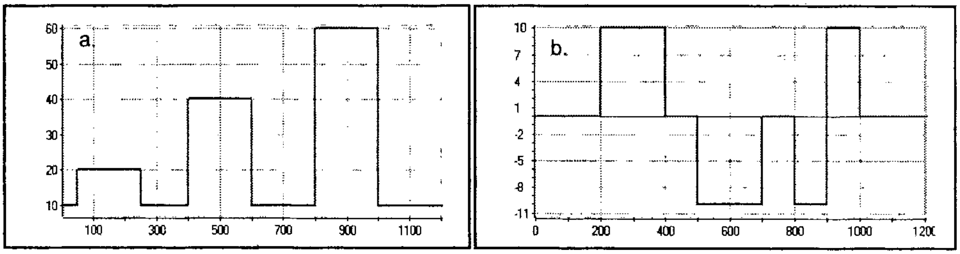

Fig.4. Transients of signals at testing: a) a reference value w_t, b) a disturbance d_t

where reactions of the closed-loop control on steps of the reference value were recorded and evaluated. These steps have corresponded to 20, 50 and 80% of maximal output value of the closed loop-system. The performance index was defined as follow

$$I_R = \sum_{t=1}^{N=1200} | w_t - y_t | \cdot \tag{17}$$

The aim of next test was evaluation a compensation abilities in a closed-loop system at disturbance signal set to the output. To make simulation conditions more real, the impact of disturbance was modelled as an output of low pass filter, Fig. 4b. The transfer function of the low pass filter was equal

$$F(s) = \frac{K}{1+sT} \qquad K = 1, \qquad T = 4s$$

with reference value w_t was equal w_0. The corresponding performance index was equal

$$I_D = \sum_{t=1}^{N=1200} | w_0 - y_t | \cdot \tag{18}$$

4.3. Presentation of results

Modifications of PID algorithm, described in section 2, usually demanded fitting some additional parameters. In case of TF-PID algorithm one could try to: fit two variable parameters T_V, ρ within some ranges, choose a method for conditioning of integration (C1 – C4) and next set values $V1$ or $E1$. A comparison of all combinations would be too extensive, hence for each algorithm only the best version (in sense of I_R) was shown in Tables and the optimal parameters of this algorithm were presented.

As the first, in all Tables, were shown results for ideal I-PID algorithm (together with optimal settings K, T_I T_D and gain margin ΔK) with no constraints set on the controller output – i.e. actuator could follow each output value of the controller. In the second row were shown results obtained for the same controller with constraints of the actuator output and velocity, denoted as S-PID. The results of R-PID are presenting efficiency of usual used algorithm (6) with optimised value of $\kappa = T_D/T_V$. The algorithm, based on transfer function (7) with conditional integration halted according to conditions C1-C4 (tested all cases), optimal tuned parameters c_1 and ρ, was denoted as TF-PID. The back-calculation approach (8), with optimised $\tau = T_t/T_I$, was marked as BC-PID. The comparison was completed with proposed algorithm with dynamic modification of reference value DM-PID. Together with calculated performance indices a number m_p of tuned or inspected parameters will be shown.

Table 4.1 Results for optimal choice a PID algorithms for Process 1_5

Type of algorithm	Index I_R	I_R/I_{R0}	Index I_D	I_D/I_{D0}	Number m_p	Parameters of optimal version of tested algorithm and comments
I-PID I_{R0}, I_{D0}	1954		828		-	no constraints, $K=0.292$, $T_I=25.32$s, $T_D=4.615$s, $\Delta K=6.3$ dB
S-PID	4994	2.56	1964	2.37	-	$v_t \in <0,10>$, $\Delta v/\Delta=1.0$
R-PID	4175	2.14	1428	1.73	1	$v_t \in <0,10>$, $\Delta v/\Delta=1.0$, $\kappa=4.72$
TF-PID	4233	2.17	1824	2.20	4	$v_t \in <0,10>$, $\Delta v/\Delta=1.0$; $E1=0.82$, $c_1=0.0$, $\rho=0.98$
BC-PID	3872	1.98	1442	1.74	1	$v_t \in <0,10>$, $\Delta v/\Delta=1.0$, $\tau=0.52$
DM-PID	3946	2.02	1369	1.65	-	$v_t \in <0,10>$, $\Delta v/\Delta=1.0$,

The best result has provided the I-PID controller with no constraints on actuator output. The value of $I_{R0}=1954$ was low and the quality of control is shown on Fig. 5a. A control algorithm, with no tool to cope with wind-up effects, (Fig.5a) realised by S-PID has yielded poor results (I_R index was ≈260% increased with respect to I_{R0}). The classic industrial applied algorithm R-PID, with separated actions (P, I, D) and optimised T_V has achieved index of 210% of optimal value I_{R0}. A TF-PID algorithm has gained a moderate success – it was better then S-PID but worse then optimal R-PID. The best ratio I_R/I_{R0} (of all described algorithms) has achieved back calculation algorithm (BC-PID) with parameter $\tau=0.52$, Fig.5b. This very good result has been involved by reduc

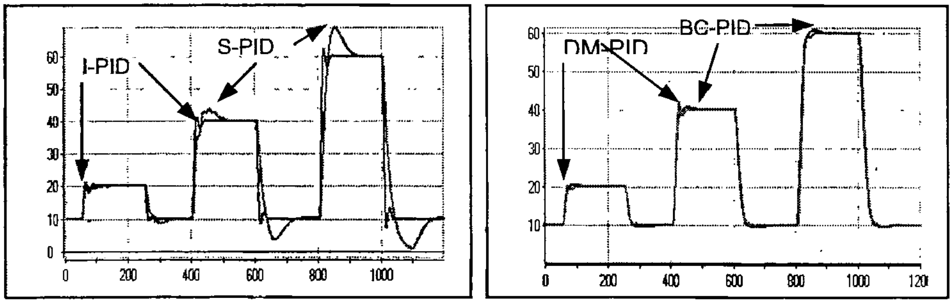

Fig.5. Results of control for system P1_5: a) I-PID, S-PID, b) DM-PID and BC-PID.

tion of I term in case of saturation in actuator. This action is not induced in proposed DM-PID algorithm and therefore it has little overshoot (see Fig.5b).

The ratio I_D/I_{D0} is very important index too. In many applications, this parameter is even more significant than I_R/I_{R0}. A comparison of this factor has shown quite interesting results. Transfer function controller TF-PID was only little better than S-PID. This fact was probably induced by difficulties in separation of I action in form of TF-PID (7). The best was DM-PID, though BC-PID reaction was not very far from DM-PID results.

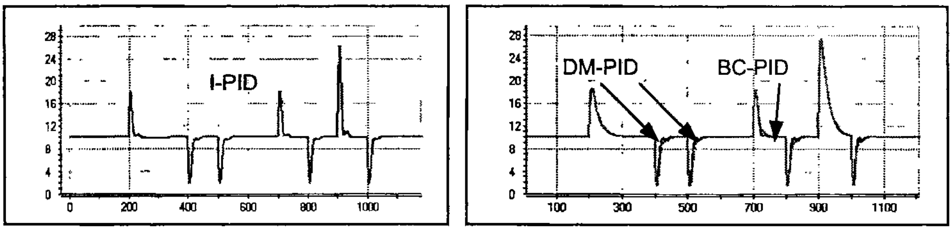

Fig.6. Control at disturbance impact for P1_5 a) I-PID, b) DM-PID and BC-PID

The delay d=11, for process P1_11, was more demanding task for the controller algorithms. In previous case the corresponding performance rational indices I_R/I_{R0} and I_D/I_{D0} were greater, due to small values of I_{R0} and I_{D0}, Table 4.2 At delay d=11 even ideal controller I-PID has a slip in reaction, hence values of I_{R0} and I_{D0} were increased

Table 4.2 Results for optimal choice a PID algorithms for Process 1_11

Type of algorithm	Index I_R	I_R/I_{R0}	Index I_D	I_D/I_{D0}	Number m_p	Parameters of optimal version of tested algorithm and comments
I-PID I_{R0}, I_{D0}	3612		1592		-	no constraints, K=0.170, T_I=25.71s, T_D=6.273s, ΔK=6.1 dB
S-PID	6264	1.73	2587	1.63	-	$v_t \in <0,10>$, Δv/Δ=1.0
R-PID	5261	1.46	2071	1.30	1	$v_t \in <0,10>$, Δv/Δ=1.0, κ=6.45
TF-PID	5484	1.52	2686	1.69	4	$v_t \in <0,10>$, Δv/Δ=1.0; E1=1.0, c_1=0.0, ρ=0.95
BC-PID	5297	1.47	2084	1.31	1	$v_t \in <0,10>$, Δv/Δ=1.0, τ=0.41
DM-PID	5194	1.44	2017	1.27	-	$v_t \in <0,10>$, Δv/Δ=1.0,

The conclusions from Table 4.2 are close to observed in Table 4.1. The best was DM-PID (best for both indices) and the second was R-PID followed very close by BC-PID. The TF-PID algorithm has failed. Responses are shown on Fig.7. The proposed DM-PID algorithm has faster "come back" to the reference value then BC-PID and R-PID. Both algorithms BC-PID and R-PID, have one tuned parameter.

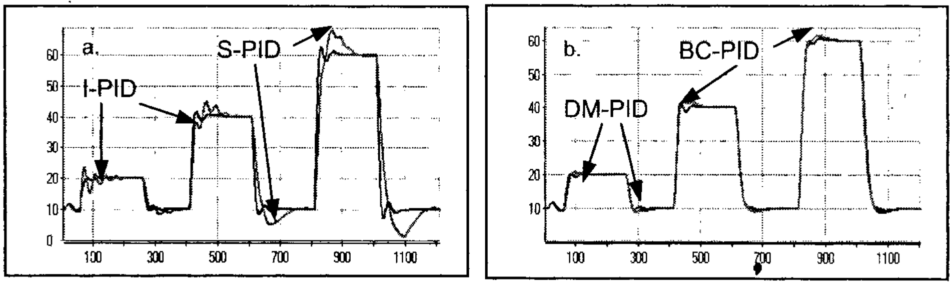

Fig.7. Results of control for system P1_11: a) I-PID, S-PID, b) DM-PID and BC-PID.

Control of process P2 (16) was a real challenge for PID controllers. The big gain can yield nervous closed-loop behaviour and gain margin ΔK can be small. These problems can be observed by investigation of controller I-PID gain factor K, (Table 4.3), that was much less in comparison to the process P1_5. Some reduction of gain can be expected, because of static gain factor equal 20, but still it was quite small $K_{I\text{-}PID}$ =0.066. For the shown choice of I-PID controller settings, the closed-loop system has quite sufficient gain margin equal 6.8 dB. The low controller gain has introduced long reaction phase of controller for both investigated cases; change of reference input and disturbance impact.

The testing was performed as in case of Process 1, but only for one delay d=5. This time the actuator constraints were set to $v_t \in <0, 5>$ (for static gain of process P2 it was enough) and $\Delta v/\Delta$= 20%. The minimal performance indices I_{R0}= 4703 and I_{D0} = 2023 were for this process high, hence resulting values of ratio I_R/I_{R0} and I_D/I_{D0} were low.

Table 4.3 Results for optimal choice a PID algorithms for Process 2

Type of algorithm	Index I_R	I_R/I_{R0}	Index I_D	I_D/I_{D0}	Num ber m_p	Parameters of optimal version of tested algorithm and comments
I-PID I_{R0}, I_{D0}	4703	.	2023		-	no constraints, K=0.066, T_I=30.29s, T_D=9.038s, ΔK=6.8 dB
S-PID	8207	1.75	3312	1.64	-	$v_t \in <0,10>$, $\Delta v/\Delta=1.0$
R-PID	7137	1.52	2571	1.27	1	$v_t \in <0,10>$, $\Delta v/\Delta=1.0$, $\kappa=9.20$
TF-PID	7741	1.65	3629	1.79	4	$v_t \in <0,10>$, $\Delta v/\Delta=1.0$; C2 for E1=1.0, $c_1=0.0$, $\rho=1.05$
BC-PID	6857	1.46	2647	1.31	1	$v_t \in <0,10>$, $\Delta v/\Delta=1.0$, $\tau=0.21$
DM-PID	6001	1.28	2506	1.24	-	$v_t \in <0,10>$, $\Delta v/\Delta=1.0$,

Each controller has to cope with control task and non-minimalphase dynamics of process. It has induced mentioned low gain factor and slow control. The conventional algorithm R-PID, with separated actions, optimised κ and limited integral action (when saturation of actuator had appeared) was quite effective. Even better then BC-PID, for disturbance rejection, but the best was again DMR-PID modification, what can be observed on plots Fig. 8. Its action was very alike I-PID with small delay. Algorithm BC-PID was not so exact and fast. Rejection of disturbance impact was in case of DMR-PID quite satisfactory too. Controller was trying to be as fast as possible within introduced constraints.

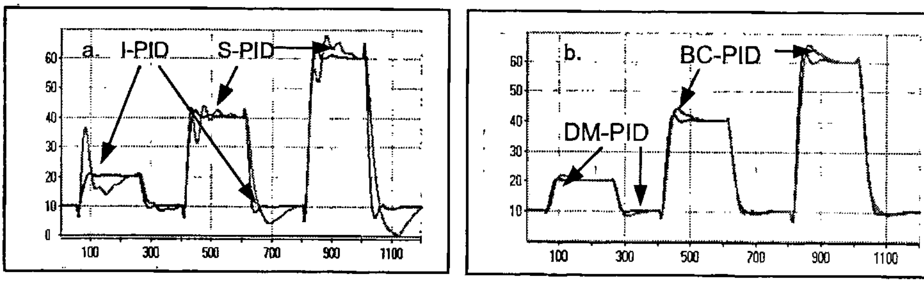

Fig.8. Results of control for system P2: a) I-PID, S-PID, b) DM-PID and BC-PID.

5. CONCLUSIONS

The presented tests, for different modifications of basic PID of algorithm, can yield some reflections. The considered techniques preventing windup effect, based on modification (cease or even decrease) of integral action of controller in case of actuator saturation are always connected with some choice of conditions C1-C4. A more or less subjective choice of corresponding parameters, e.g. E1 or V1, that has to be fitted to individual case will not be good for both activities of controller; following the reference value and compensation of disturbance impact.

The algorithm R-PID, usually used in industrial controllers, is quite good and very significant improvement can not be expected with presented simple means. But even a small profit in this area, considering a very large number of applications, should be interesting. The separate R-PID controller actions, together with permissible area for integral term and inertia introduced in derivative term, are very efficient and easy at implementation. On the contrary, introduction of the different conditions and non-linear acting modifications in transfer function form of controller TF-PID, with necessary condition of bump-less action has rather deteriorate, then improve their efficiency in the closed-loop system.

The other approach to windup problem, based on reduction of integral action term in case of actuator saturation, introduced in BC-PID, is quite prospective, but not always better then R-PID (see Tabl. 4.1 and 4.2 – a ratio I_D/I_{D0}).

The presented approach of dynamic modification of reference value, DM-PID, is based on other idea. In short words it can be summarised as follow; create the controller-actuator pair conditions, that they can always work without constraints. This approach was in all cases better than R-PID and demand less care at implementation – it has no tuned parameters. In one case BC-PID was better than DM-PID, but BC-PID has to be optimised (parameter τ). The mentioned case of BC-PID supremacy was connected with reference value alternation, when saturation of actuator is long and reduction of integral term action can be efficient. An introduction of this tool, for anti-windup battle in controller, can be further investigated, but will probably need some tuning, that is not recommended in adaptive applications.

An implementation of presented DM-PID modification is quite easy. The permissible changes on controller output Δv_{-}, Δv_{+}.(12), (13) have to be determined and the modification of reference value (14) has to be set into algorithm. It does not need many alter in a basic controller code and can be easy implemented in PLC devices. The necessary data are composed of direct constraints of each actuator and can be individually fitted to any, even asymmetrically working control instrument. The proper settings of PID control algorithm can be optimised with some software tool or determined via special designed experiment [2,3,6,8].

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