Pole placement based design of PIDC controller under constraint on robustness

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Abstract—**This paper presents an effective design method of PID controller with series differential compensator ie. PIDC controller. The adjustable parameters of a PIDC controller are: proportional gain k_p, integral gain k_i, derivative gain k_d, the second order derivative gain k_h and filter time constant T_f. The proposed design procedure is based on pole placement to approximately obtain dynamics of the closed loop system defined with the poles of the criterion test function which has optimal performance in sense of minimal settling time without overshoot. The design goal is to obtain good load disturbance response with constraint on robustness, so parameter k_p is selected to guarantee desired robustness given in the form of closed loop maximum sensitivity M_s and considering sensitivity to the measurement noise M_n. This technique is applicable to a wide range of transfer functions: stable and unstable, with and without time-delay, rational and non-rational and those describing distributed parameters. Validity of a proposed method is verified through a series of numerical simulations of processes typically encountered in industry.**

Keywords- PIDC controller, Robustness, Performance; Pole spectrum; Load disturbance rejection;

I. INTRODUCTION

More than 95% control loops in process industry are of PI or PID type [1], while in oil industry this percentage is 97% [2]. Survey in [3] classifies PID controller as the second contribution in the instruments of 20th century used for control, decision and communication, right behind microprocessor. In industrial practice many of PID controllers are poorly tuned, in [4] on the basis of "extensive industry testing" is claimed that 75% PID based control loops are out of tune, while in [5] is reported that 25% control loops with PID controllers use default settings, implying that they have not been tuned at all. In order to make greater impact on industrial practice in process control with better accessibility of tuning rules, O'Dwyer summarizes in [5] many PI/PID tuning formulae in unified notation.

During last decade and a half, different optimization procedures of PID controllers are developed [6-22]. Most of them are complex and based on achievement of trade-off between different requirements elaborated in [18] to get better performance and robustness indices with smaller sensitivity to the measurement noise.

Additional improvement of performance and robustness of the control loops can be obtained with extension of PID controller with series differential compensator ie. PIDC controller. Some recent works [23-35] dealing with these issues are characterized with simplicity and computational efficiency to obtain good load disturbance attenuation. These methods use some of the optimization methods to obtain minimum of IAE (Integrated Absolute Error) considering the robustness constraints. Next to that, fractional PIDC$^{\alpha}$ is introduced in [26] to get performance/robustness improvements in comparison with conventional PID.

Addition to the above, an effective and still popular method to handle with control of linear stationary systems is pole placement. The idea to achieve desired performance is to select adequate dominant poles, which determine the behaviour of the closed loop dynamics. The dominance of these poles can be ensured with different methods such as root-locus or Nyquist stability criteria used in [27], D-decomposition method as in [28,29] etc. Let be noted that in [27] root locus procedure is used for the systems with no transport delay in process model, while for systems with delay Nyquist stability criteria must be used. However, recently in [30] generalized root-locus method is proposed regardless of the open loop transfer function.

The proposed tuning method gives closed-loop system load disturbance and reference response with predictable properties. The design procedure is based on criterion test function having optimal performance in terms of minimal settling time and without overshoot. For assigned filter time constant, pole placement method gives three parameters of PIDC controller as linear functions of the fourth, e.g. proportional gain k_p. The aim of the work is to guarantee desired robustness given in the form of maximum sensitivity M_s, while good performance is obtained on the basis of selection of dominant poles. As an indicator of desired performance it can be used estimated settling time with minimal overshoot. Finally, presented tuning algorithm is analysed via numerical simulations on wide class of plants typically encountered in process industry.

II. DESIGN PROCEDURE OF PIDC CONTROLLER

The control system architecture is presented in Fig. 1, where $G_p(s)$ is the process transfer function, $C_{PIDC}(s)$ is PIDC controller transfer function and $G_{ff}(s)$ describes feed-forward from the reference r to the control signal u. Load disturbance at the input of a process, the measurement noise and output signal are denoted with d, n and y, respectively.

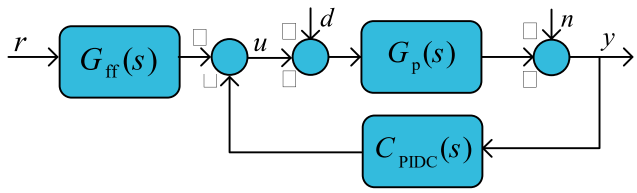

Figure 1. The control system structure with controller C_{PIDC} and process G_p

The loop transfer function $L(s)$ for the system in Fig. 1. is

$$L(s) = \gamma \frac{k_h s^3 + k_d s^2 + k_p s + k_i}{s(\frac{1}{2}T_f^2 s^2 + T_f s + 1)} G_p(s) = C_{PIDC}(s) G_p(s) \quad (1)$$

where k_p, k_i, k_d, k_h are adjustable parameters of PIDC controller and T_f is a time contant of the second order filter with damping ratio $\zeta = 1/\sqrt{2}$. If the static gain of the process $G_p(s)$ is positive then parameter $\gamma = 1$, while for negative static gain is $\gamma = -1$.

For a given plant $G_p(s)$, the closed loop characteristic function of the system in Fig. 1. is

$$f(s) = 1 + C_{PIDC}(s) G_p(s) \quad (2)$$

Positions of the dominant poles of the closed loop system can be obtained by specifying its desired performance requirements such as settling time and overshoot as in [29]. However, in this paper, pole locations are determined with respect to the criterion test function $F_{test}(s)$. For PIDC controller $F_{test}(s)$ is a third order transfer function defined as

$$F_{test}(s) = \frac{1}{(s/\zeta + 1)(s^2 + 2\zeta s + 1)} \quad (3)$$

with damping ratio $\zeta = 1/\sqrt{2}$ to select optimal performance in terms of minimal settling time t_s without overshoot. Dominant poles are now defined in terms of poles s_i of criterion test function as follows

$$p_i = \frac{\omega_u}{\alpha} s_i, i = 1, 2, 3 \quad (4)$$

where ω_u is a process ultimate frequency and $\alpha \le 1$ is a free parameter to additionaly adjust pole location. For specified value of α dominant poles in (4) are obtained and can be further written down as $p_{1,2} = \sigma_d \pm j\omega_d$ and $p_3 = \sigma_d$. By substituting one of complex poles (e.g. p_1) and real pole p_3 in (2) we obtain following equations

$$k_h p_1^3 + k_d p_1^2 + k_p p_1 + k_i = -p_1 \frac{\frac{1}{2}T_f^2 p_1^2 + T_f p_1 + 1}{G_p(p_1)} \quad (5)$$

$$k_h p_3^3 + k_d p_3^2 + k_p p_3 + k_i = -p_3 \frac{\frac{1}{2}T_f^2 p_3^2 + T_f p_3 + 1}{G_p(p_3)} \quad (6)$$

Now, equation (5) is separated to real and imaginary part which together with equation (6) gives three linear equations with respect to k_p, k_i, k_d and k_h. For assigned filter time constant $T_f = 1/(N\omega_u)$, $N \in (2,10)$ these three equations can be solved for k_i, k_d, k_h as linear function of k_p as follows in (7)

$$k_i = -\frac{\sigma_d(\sigma_d^2 + \omega_d^2)}{(3\sigma_d^2 + \omega_d^2)} k_p + \frac{\sigma_d(\sigma_d^2 + \omega_d^2)(\sigma_d^2 U_1 - (\sigma_d^2 + \omega_d^2)U_2 + \sigma_d \omega_d V_1)}{\omega_d^2 (3\sigma_d^2 + \omega_d^2)},$$

$$k_d = -\frac{3\sigma_d}{3\sigma_d^2 + \omega_d^2} k_p - \frac{\sigma_d(3\sigma_d^2 + 2\omega_d^2)U_1 + \omega_d^3 V_1 + \sigma_d(\omega_d^2 - 3\sigma_d^2)U_2}{\omega_d^2(3\sigma_d^2 + \omega_d^2)},$$

$$k_h = \frac{1}{3\sigma_d^2 + \omega_d^2} k_p + \frac{(2\sigma_d^2 + \omega_d^2)U_1 - \sigma_d \omega_d V_1 + 2\sigma_d^2 U_2}{\omega_d^2(3\sigma_d^2 + \omega_d^2)},$$ wherein

$U_1 = \mathrm{Re}\{(\frac{1}{2}T_f^2 p_1^2 + T_f p_1 + 1)/G_p(p_1)\}$, $U_2 = (\frac{1}{2}T_f^2 p_3^2 + T_f p_3 + 1)/G_p(p_3)$,

and $V_1 = \mathrm{Im}\{(\frac{1}{2}T_f^2 p_1^2 + T_f p_1 + 1)/G_p(p_1)\}$.

Now, by simple rearrangements of (2) with obtained functions $k_i = k_i(k_p)$, $k_d = k_d(k_p)$, $k_h = k_h(k_p)$, we can obtain an auxiliary characteristic equation equivalent to (2), with k_p, as the only free parameter

$$1 + k_p \hat{W}(s) = 0 \quad (7)$$

Let us note that auxiliary transfer function $\hat{W}(s)$ is non-rational function for time-delayed systems. In order to ensure dominance of poles p_n it can be used idea from [27] to locate all the other poles of the closed loop system at the left of line $m\sigma_d + j\omega$ and $m \ge 1$. However, here k_p is selected under conditions (5) and (6) to guarantee desired robustness and good load disturbance of the system while dominance condition $m \ge 1$ is fulfilled for the most of the processes.

An auxiliary design guideline is expected settling time t_s. On the basis of the simulated step response of the test function $F_{test}(s)$ normalized 1% settling time t_n=6.5886 sec is obtained. Hence, 1% settling time of the closed loop system with controller $C_{PIDC}(s)$ in Fig. 1 can be approximated with

$$t_s^{est} = 6.5886 \frac{\alpha}{\omega_u} + L \quad (8)$$

where L is the plant dead time. Performance is usually measured by the integrated absolute error IAE [31]:

$$IAE = \int_0^\infty |y_d(t)| dt \quad (9)$$

wherein $y_d(t)$ is the response of the system to a unit step load disturbance $d(t)$. For well damped systems IAE is reduced to IE=1/k_i. As the measure of the robustness it is used the maximum M_s of the sensitivity function of the closed loop system ie. $M_s = \max_{\omega} |1/(1+L(j\omega))|$, while sensitivity to the modelling errors is characterized by the maximum M_p of the complementary sensitivity function defined as $M_p = \max_{\omega} |L(j\omega)/(1+L(j\omega))|$. The design procedure considers maximal sensitivity to the measurement noise is $M_n = \max_{\omega} |-C_{PID}(j\omega)/(1+L(j\omega))|$, which due to structure of PIDC controller attain at high frequencies ie. $M_n \approx M_{n,\infty} = 2|k_h|/T_f^2$.

III. Analysis and Evaluation of the Proposed Design Method

The proposed design method is applied to process models typically encountered in process control. The test batch includes stable, integrating, non-minimum phase, oscillating and unstable plant and a distributed parameter process [6,13-14]:

$$G_{p1}(s) = \frac{2e^{-s}}{(10s+1)(5s+1)},\ G_{p2}(s) = \frac{1}{(s+1)^4},$$

$$G_{p3}(s) = \frac{1}{\prod_{k=0}^{3}(0.7^k s+1)},\ G_{p4}(s) = \frac{e^{-s}}{(s+1)^2},\ G_{p5}(s) = \frac{e^{-5s}}{(s+1)^3},$$

$$G_{p6}(s) = \frac{1-s}{(s+1)^3},\ G_{p7}(s) = \frac{(2s+1)e^{-4s}}{(10s+1)(7s+1)(3s+1)}.$$

$$G_{p8}(s) = \frac{1}{s(s+1)^3},\ G_{p9}(s) = \frac{e^{-s}}{s^2+0.1s+1},\ G_{p10}(s) = \frac{e^{-0.5s}}{s},$$

$$G_{p11}(s) = \frac{1}{\cosh\sqrt{2s}},\ G_{p12}(s) = \frac{1}{(s+1)(0.25s^2+0.7s+1)},$$

$$G_{p13}(s) = \frac{4e^{-2s}}{4s-1},\ G_{p14}(s) = \frac{e^{-0.5s}}{(5s-1)(2s+1)(0.5s+1)},$$

The control signal in Fig. 1. is realized as

$$u(t) = k_p(br(t) - y_f(t)) + k_i \int (r(t)-y_f(t))dt - k_d \frac{dy_f(t)}{dt} - k_h \frac{d^2 y_f(t)}{dt^2}$$

wherein $b \in [0,1]$ is used for set point weighting as in [32], and y_f is filtered output signal generated by the second order noise filter.

Results of numerical simulations are presented in Fig. 2-7. In all simulations parameter b iz zero. The impact of parameter α to the process response is analysed for processes G_{p2}, G_{p3} and G_{p5} and shown in Table I with obtained parameters of PIDC controller.

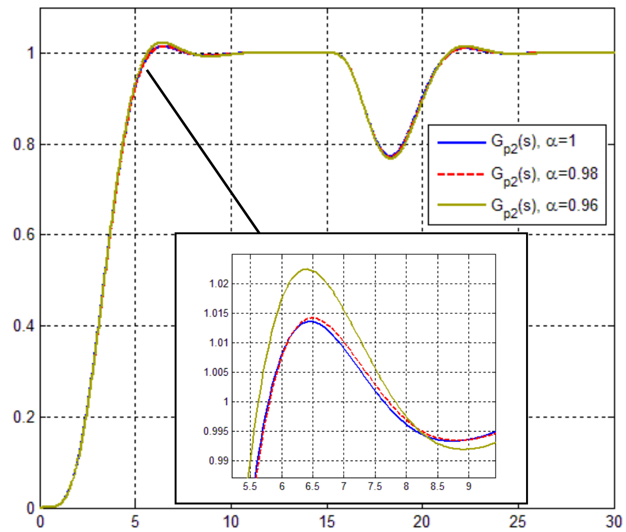

Figure 2. The reference unit step response of process G_{p2} with load disturbance $D(s)$=-1/s starting from t=15 sec

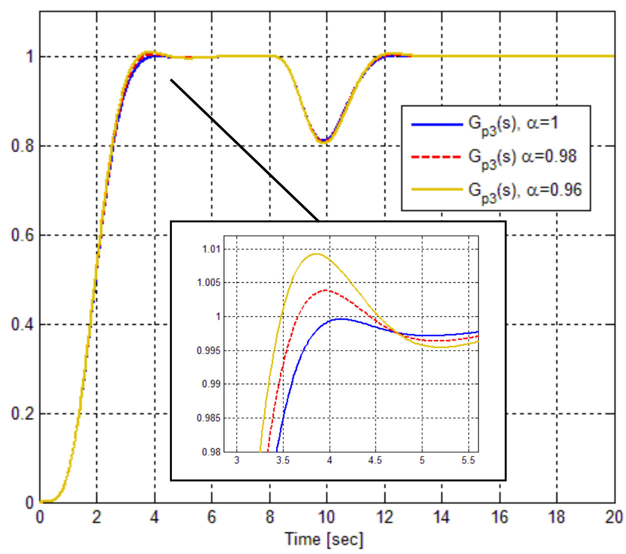

Figure 3. The reference unit step response of process G_{p3} with load disturbance $D(s)$=-1/s starting from t=8 sec

TABLE I. Parameters of PIDC controller for processes G_{Pi}, I=2,3,5 under constraint on robustness M_s=2 for α=1, α=0.98 and α=0.96 and ε=1%

Process	ω_u	α	k_p	k_i	k_d	k_h	T_f	IAE	M_n	M_s	M_p	$t_{s,\varepsilon}$ [sec]
$G_{p2}(s)$	1.0000	1.00	4.4920	1.4761	4.9548	2.1860	0.2857	0.6940	53.56	2.00	1.52	5.81
$G_{p2}(s)$	1.0000	0.98	4.4345	1.4724	4.8509	2.1155	0.2857	0.7078	51.83	2.00	1.53	7.00
$G_{p2}(s)$	1.0000	0.96	4.3674	1.4677	4.7471	2.0483	0.2857	0.7238	50.18	2.00	1.54	7.28
$G_{p3}(s)$	1.7075	1.00	5.4350	2.9591	3.5590	0.9049	0.1673	0.3396	64.64	2.00	1.53	3.59
$G_{p3}(s)$	1.7075	0.98	5.3695	2.9504	3.4900	0.8769	0.1673	0.3440	62.64	2.00	1.54	3.45
$G_{p3}(s)$	1.7075	0.96	5.3080	2.9436	3.4259	0.8513	0.1673	0.3491	60.81	2.00	1.56	3.35
$G_{p5}(s)$	0.4000	1.00	0.7908	0.1479	1.5829	1.3611	0.8333	7.3071	3.92	2.00	1.06	21.69
$G_{p5}(s)$	0.4000	0.98	0.7845	0.1477	1.5559	1.3109	0.8333	7.3772	3.77	2.00	1.07	22.05
$G_{p5}(s)$	0.4000	0.96	0.7780	0.1474	1.5295	1.2643	0.8333	7.4442	3.64	2.00	2.07	22.34

Process G_{p2} is a typical process with balanced dynamics. Estimated settling time from (8) is 6.59 s. For same robustness constraint M_s=2 and three values of α, small IAE is obtained, and settling time around the estimated. The same treatment is repeated for other two representatives of process dynamics: process G_{p3} with lag-dominated dynamics and process G_{p5} with delay-dominated dynamics. It can be concluded from enlarged parts of Figs 2-4 that small decrease in parameter α leads to faster response ie. smaller rise time and larger overshoot. For process G_{p2} overshoot is less than 1.5% for α=1 and α=0.98, while for G_{p3} there is no overshoot for α=1. It is also obvious that under the same robustness constraint M_s, smaller α leads to larger IAE. For processes G_{p2} and G_{p5} smaller α corresponds to larger settling time t_s, while for process G_{p2} settling time t_s is smaller due to low amplitude oscillations are less than 1% of response stationary value. Finally, response of the system with process G_{p5} characterizes with overshoot of around 3% and settling time slightly greater than estimated 21.47 sec. It is obvious that parameter α leads to greater changes in reponse dynamics for plants for longer dead time.

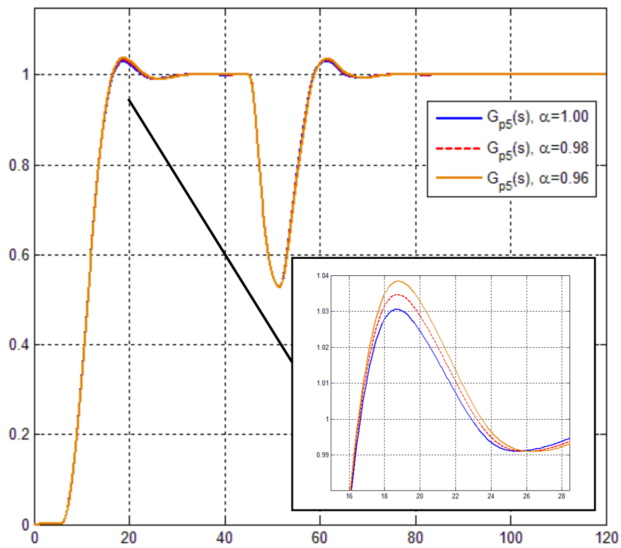

Figure 4. The reference unit step response of process G_{p5} with load disturbance $D(s)$=-0.5/s starting from t=40 sec

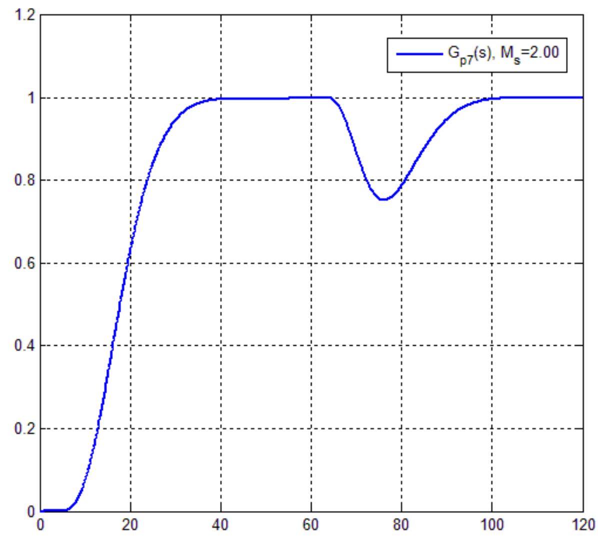

Figure 5. The reference unit step response of process G_{p7} with load disturbance $D(s)$=-1/s starting from t=15 sec

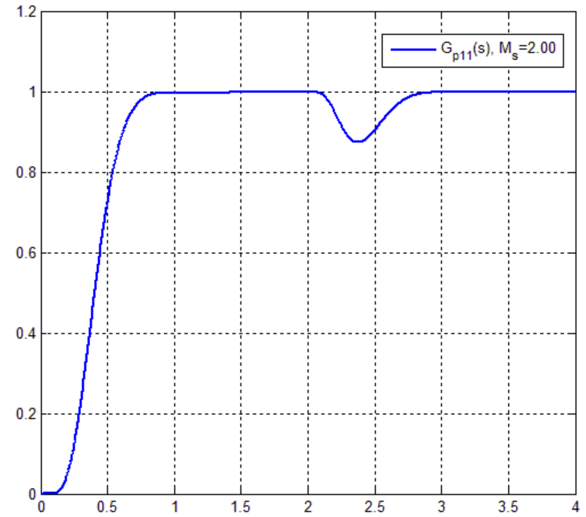

Figure 6. The reference unit step response of process G_{p11} with load disturbance $D(s)$=-1/s starting from t=15 sec

TABLE II. PARAMETERS OF PIDC CONTROLLER FOR PROCESSES G_{pi}, I=1,4,6-14 UNDER CONSTRAINT ON ROBUSTNESS M_s FOR FIXED α=1 AND ε=1%

Process	ω_u	k_p	k_i	k_d	k_h	T_f	IAE	M_n	M_s	M_p	$t_{s,\varepsilon}$ [sec]
$G_{p1}(s)$	0.5389	7.550	1.1459	16.0989	5.7647	0.3711	0.8727	83.69	2.00	1.64	13.61
$G_{p4}(s)$	1.3065	1.858	0.8380	1.3211	0.3136	0.1531	1.2011	26.76	2.00	1.22	5.58
$G_{p6}(s)$	1.0000	1.3810	0.4826	1.2916	0.4039	0.2000	2.3391	20.19	2.00	1.21	8.68
$G_{p7}(s)$	0.2144	3.9730	0.2553	19.8947	31.1277	0.9328	3.9168	71.54	2.00	1.36	36.05
$G_{p8}(s)$	0.5773	1.3750	0.2307	2.4970	1.6975	0.3464	4.3393	28.29	2.00	1.55	11.64
$G_{p9}(s)$	1.0304	-0.3340	0.1279	0.1986	0.0812	0.1941	7.8206	4.31	2.00	1.00	10.93
$G_{p10}(s)$	3.1416	1.3700	0.5529	0.1999	-0.00844	0.0637	1.8087	4.17	2.00	1.47	7.08
$G_{p11}(s)$	9.8696	8.6280	21.7326	0.8679	0.02533	0.0253	0.0461	79.26	2.00	1.54	0.79
$G_{p12}(s)$	2.6077	18.5430	15.5706	8.2281	1.6085	0.0959	0.0642	350	2.00	1.45	2.59
$G_{p13}(s)$	0.5828	0.6413	0.0596	0.7772	0.3611	0.4902	16.8626	3.00	4.00	3.27	11.96
$G_{p14}(s)$	0.4287	5.4890	0.6022	12.1107	8.6620	0.4665	1.6608	79.75	3.00	2.09	15.56

Obtained parameters of PIDC controller and corresponding performance/robustness constraints for processes G_{pi}, i=1,4,6-14 are presented in Table II. Proposed tuning method in comparison with max(k_i) and max(k) methods applied to PIDC controller reported in [23] and fractional PIDC$^{\alpha}$ in [26] gives smaller IAE for the same M_s.

IV. Conclusions

The design problem of PIDC controllers under constraint on robustness for typical industrial processes on the basis of pole placement is analysed. PIDC controller is designed to obtain good load disturbance response by minimizing the integrated absolute error IAE. Sensitivity to the measurement M_n noise can be decrease with higher values of time constant of noise filter and is related with the second order derivative gain of PIDC controller. In addition to PIDC parameters, a free parameter α can be selected in order to make reponse faster at the expense of increase of IAE under the same robustness. When compared to the recent max(k_i) and max(k) methods applied to PIDC and PIDC$^{\alpha}$ controller [23,26], the proposed novel tuning method gives smaller IAE under the same robustness constraint M_s.

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