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The autotuned dead-time compensating control system with improved disturbance rejection

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Abstract: This paper presents the concept of auto-tuned control system with modified Smith Predictor that can be used as an effective dead-time compensator. For better disturbance rejection capability the system is equipped with an additional feedback loop and is extended to cascade structure. Several tuning rules for the master controller are presented. The article also includes the results of simulations for two particular configurations of the system structure..

Keywords: cascade control, delay compensation, inverse dynamics control, time-delay estimation

1. INTRODUCTION

Industrial processes as well as engineering, economic and biological systems commonly exhibit time delays or dead-times. The dead-time complicates the analysis and design of control systems and makes satisfactory control more difficult. The control in a closed-loop system of a time-delayed process using a single feedback loop requires a strong reduction of the gain of the open-loop system which leads to the slowdown of the whole system as well as very sluggish response. The solution to this problem may be systems that eliminate measurement delays, such as Smith predictor (SP) or its subsequent modifications. These systems are able significantly improve the set-point tracking as well as remain indifferent to their ability of the disturbance rejection. In recent 20 years a few modifications of SP were presented. However, only a few of them were devoted to the problem of increasing system ability of the disturbance rejection. Some of them are described by Normey-Rico and Camacho in their survey (2008). Matausek and Micic (1996) have shown that by adding an additional gain the disturbance response of SP can be controlled independently to the set point response. The problem of automatic tuning in Smith Predictor configuration was presented by Kaya (2003) and Majhi (2007).

2. PROBLEM STATEMENT

The concept of control of time-delayed processes presented in this paper is based on a strategy to compensate time delay in the feedback loop, which will allow quicker react for changes of the controlled variable.

Let's consider a process which model is given by the transfer function $P(s)= P_1(s)\ P_2(s)\ \exp(-Ls)$. The variable y_1 is the output of the first fast part of the plant, y is the controlled variable that at the same time is the output of the part $P_2(s)$ which represents the slow dynamics of the plant. The closed-loop transfer function mentioned as a relation of output transform *y(s)* to reference signal *r(s)* taking into account the dead-time compensator can be formulated as

$$G(s) = \frac{C(s)\cdot P_1(s)P_2(s)\cdot e^{-Ls}}{1 + C(s)P_m(s)(1-e^{-L_m s}) + C(s)P_1(s)P_2(s)\cdot e^{-Ls}} \qquad (1)$$

Assuming exact matching between the process and the model parameters, it's

$$P_m(s)=P_1(s)\ P_2(s) \quad \text{and} \quad L_m = L \qquad (2)$$

the set point response can be derived as

$$G(s) = \frac{y(s)}{y_r(s)} = \frac{C(s)\cdot P_1(s)P_2(s)\cdot e^{-Ls}}{1 + C(s)\cdot P_m(s)} \qquad (3)$$

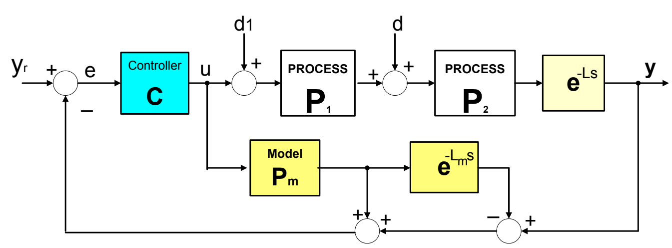

Fig. 1. Control system with Smith Predictor

and the disturbance signal response as

$$G_d(s) = \frac{y(s)}{d(s)} = P_1(s)P_2(s)\cdot e^{-Ls}\cdot\left[1 - \frac{C(s)\cdot P_1(s)P_2(s)\cdot e^{-Ls}}{1 + C(s)\cdot P_m(s)}\right] \qquad (4)$$

It can be seen from the above expression that poles of $P(s)= P_1(s)\ P_1(s)$ cannot be eliminated, except for the pole at s=0. When the controller is tuned to accelerate the closed-loop set-point tracking response, the disturbance rejection does not change slightly. But when a part of disturbances affects the processes in the field of actuators it is possible to compensate their influence on the controlled variable using the cascade

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control system. For this reason the proposed control system that will be considered in this study is equipped with dead-time compensator (DTC) and based on cascade structure that provides an improved disturbance rejection.

3. CASCADE CONTROL SYSTEM

The effectiveness of the cascade control system is due to the fact that disturbances affecting the secondary loop are effectively compensated before they affect the process output y. It depends if the part of the process P_1 is faster than P_2, which inherently occurs in time-delayed processes. Assumeing that the sensor can be connected in the point between both terms and that the first part P_1 will be covered by an additional feedback loop equipped in controller $C_1(s)$. On the input of the inner loop is given a control signal $u(t)$. The task of the inner controller is to ensure suitable control signal in respect to influence of other disturbances. Introduction of the inner loop will change the dynamics of an open-loop system, which should be reflected in the decoupling loop with SP.

3.1 Inner loop with P or PI slave controller

As the inner loop controller can be used Proportional (P) or Proportional-Integral (PI) controller. The presence of an integrator in the inner loop is not strictly necessary since the null steady-state error can be assured by the outer loop.

In the proposed system a proportional controller with high gain is preferred which will provide high-speed operation and low static error. The schema of such system is shown in Fig.2

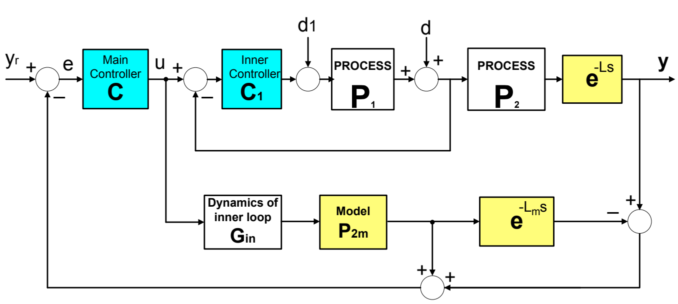

Fig. 2. Schema of control system with additional feedback

Then the transfer function of the inner loop using conventional controller will be equal to

$$G_{in}(s) = \frac{y_1(s)}{u(s)} = \frac{C_1(s)P_1(s)}{1 + C_1(s)P_1(s)} \tag{5}$$

If we take it into account and assume the perfect matching of the model and the plant the closed-loop transfer function of the DTC extended to cascade system can be derived as

$$G(s) = \frac{C(s)\cdot C_1(s)\cdot P_1(s)\cdot P_2(s)\cdot e^{-Ls}}{1 + C_1(s)P_1(s) + C(s)\cdot C_1(s)P_1(s)\cdot P_2(s)} \tag{6}$$

3.2 IMC structure of inner loop

The IMC controller is developed by Morari and Zafiriou (1989). The structure of this control system in general is shown in Fig.3.

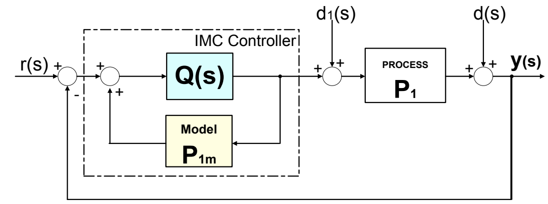

Fig. 3. The IMC controller introduced into the inner loop .

Taking into account the impact of disturbance in the system of the output y Laplace transform $y(s)$ will be equal to

$$y(s) = \frac{P_1(s)Q(s)}{1 + Q(s)[P_1(s) - P_{1m}(s)]}r(s) + \frac{1 - P_{1m}(s)Q(s)}{1 + Q(s)[P_1(s) - P_{1m}(s)]}d(s) \tag{7}$$

A two degree of freedom structure, aiming at decoupling the set-point tracking and the load disturbance rejection tasks is introduced to the IMC controller. The modified structure of the inner loop is shown in Fig.4.

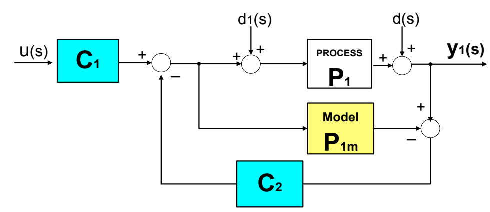

Fig. 4. The structure of inner-loop by use of IMC methodology with two degrees of freedom.

Then the output of inner loop is given by

$$y_1(s) = \frac{P_1(s)C_1(s)}{1 + C_2(s)[P_1(s) - P_{1m}(s)]}u(s) + \frac{1 - P_{1m}(s)C_2(s)}{1 + C_2(s)[P_1(s) - P_{1m}(s)]}d(s) \tag{8}$$

If they succeed to fulfill the following conditions

$$P_{m1}(s) = P_1(s) \quad \text{and} \quad C_1(s) = C_2(s) = P_1^{-1}(s) \tag{9}$$

this would imply a perfect control. Then the output of the inner loop would reproduce exact and immediately the input signal even in the presence of disturbance.

4. GENERAL TUNING PROCEDURE

The performance of SP, IMC and other model-based control strategies is affected by accuracy of the model representing the plant. Also, the tuning procedure of main controller is based on the assumption that the model used matches perfectly the plant dynamics. Therefore in this project for a model identification is indented a system that to carries out the autotuning procedure uses the single relay test (Åström, Hägglund 1984).

Because the regulating of time-delayed plants in classical control system results in large overshoot or long settling time as a criterion in the tuning process are adopted the following: non-oscillatory set-point response, limited settling time and satisfactory disturbance damping.

4.1 Master controller

The master controller is a set point tracking controller. For tuning of the control system in response to the change of reference signal is used Direct Synthesis Method. According