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Design and Simulation of Decentralized PID Controller by Direct Synthesis Method

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ABSTRACT
In this paper the design of Decentralized PID controller for TITO systems is discussed. The design of decentralized controller based on direct synthesis and detuning is presented here. Here the higher order controller is obtained and reduced into PID form using Maclaurin series approximation .The well tuned parameters of the decentralized PID controllers are achieved for various process simulation is done ,this simulation examples show the effectiveness of the controller based on the direct synthesis method. The algorithm presented in the work is tested for two input two output systems. The performance obtained by proposed algorithm is compared with the existing available methods. The method uses Maclaurin series expansion which is simple and straight forward. As the method is based on direct synthesis approach the performance of the system depends on detuning factor. After simulation it is observed that proposed controller has better performance as compared to others and they also have less interactions.

Keywords: Decentralized PID controller, Two Input Two output systems, Interactions, Direct synthesis, Detuning factor, Maclaurin Series

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INTRODUCTION

Proportional Integral Derivative (PID) controllers are most widely used controllers in the industry due to advantages such as simple structure , easy to understand the three actions and ease of implementation. About 95% or more controllers in different industries are PI or PID uo to last decade, this is according to Astrom and Hagglund [1]. However, there is not an easy way to find out the optimum parameters of the PID controller. The Ziegler – Nichols frequency response method & other tuning methods use only a small amount of information about the systems and often do not provide optimum tuning of the controllers ([3]-[7]). Tuning of PID controllers on Gain and phase margin [GPM] specifications is reported in ([8]-[12]).In this GPM the solutions are obtained numerically or graphically by trial and error methods. For systems having infinite phase crossover frequencies GPM methods are of no use.Many controller tuning rules proposed in the literature are not having any impact on industrial practices [2]. Bristol proposed the relative gain array to decide the pairings [5]. However RGA is dependent on steady state parameters of the process and are unable to give information in the dynamic region . For the PID controller only three parameter can be specified, so that conventional constrained optimization techniques may not be employed to obtain a closed form solution for the robust control schemes [18]. For complex or multivariable systems useful or mathematical models are obtained by an empirical ways [19]. The model obtained by this method is not an exact replication of the process. The problem of establishment of the structure of the controller is solved by many techniques such as manual design of expert controllers [20] and qualitative model based approach [21]. If the process model of the multivariable system is available ,then to find detuning factor for multiloop PI tuning , Luben suggested a systematic procedure in his literature [22]. But when interactions are significant then multiloop PID controller design method is unable to give acceptable responses. In order to obtain the good response there are two approaches first is to develope a full matrix PID controller. This method has deficiencies like it is difficult to design each loop independently due to cross couplings of the process channels. Again 3np parameter should be tuned , where ‘n’ is the number of inputs and ‘p’ is the number of outputs. In order to ensure the stability, many multiloop controllers in the industry are tuned loosely .But this causes inefficient operation and higher energy costs are there [23]. Another approach for such systems is to use decentralized PID controller and a decoupler. This method is of great use because it allows the use of SISO controller design methods and the number of tuning parameters in this case is only 3n. Again if the actuator or sensor fails, then it is comparatively easy to stabilize the loop manually because only one loop is directly affected by failure [24]. With this scope in the paper the design of decentralized controller is discussed based on the direct synthesis method. Different control design techniques such as detuning factor methods are given by Xiong et al.[25], sequential loop closing methods presented by Loh et al.[26] and Shen and Yu [27], independent design methods given by Grosdidier and Morari [28],Skogstud and Morari [29],and equivalent transfer function methods presented by Xiang and Cai [30], Huang et al.[31] etc. had been proposed over the years. In this paper the design of decentralized PID controller for interactive delay time process is given .The direct controller synthesis approach is used to obtain the parameters of the multiloop controller's .A detuning factor for each loop is specified in terms of closed – loop time constant. The appropriate controller settings are determined using the Maclaurin series expansion and the model of the process .Here the selection of desired closed loop time constant is very important factor because the success of proposed algorithm is based on the detuning parameter. In process control systems it is very common that different process values interact, which means that the different control loops disturb each other .This problem is solved by tuning the most important loop to give good performance, while the other loop is detuned in such a way that the interaction with the first loop becomes acceptable. This solution is different from optimal. Here our goal is to develop a TITO (Two input Two output) controller which manages to decouple the control of TITO systems. The goal is also that the controller should be useful in industrial environment.

II.STRUCTURE OF MIMO SYSTEMS

The transfer function matrix for the system with n inputs and n outputs can be represented as

$$G_p(s) = \begin{bmatrix} g_{11}(s)e^{-t_{11}s} & g_{12}(s)e^{-t_{12}s} & \cdots & g_{1n}(s)e^{-t_{1n}s} \\ g_{21}(s)e^{-t_{21}s} & g_{22}(s)e^{-t_{22}s} & \cdots & g_{2n}(s)e^{-t_{2n}s} \\ \vdots & \vdots & \vdots & \vdots \\ g_{n1}(s)e^{-t_{n1}s} & g_{n2}(s)e^{-t_{n2}s} & \cdots & g_{nn}(s)e^{-t_{nn}s} \end{bmatrix}$$

… (1)

Where, g_{ij} represents the transfer function and t_{ij} represents delay time between j^{th} input and i^{th} output. As structure of the decentralized PI/PID controller is diagonal and for a process with n inputs and n outputs, n number of diagonal controllers need to be designed. The decentralized controller in the form of transfer function matrix, can be written as,

$$G_c(s) = \begin{bmatrix} G_{c11} & 0 & \cdots & 0 \\ 0 & G_{c22} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & G_{cnn} \end{bmatrix}$$

……..(2)

The closed-loop transfer function of the system between output and set-point is,

$$T(s) = \left[1 + G_p(s)G_c(s)\right]^{-1} G_p(s)G_c(s)$$

…….(3)

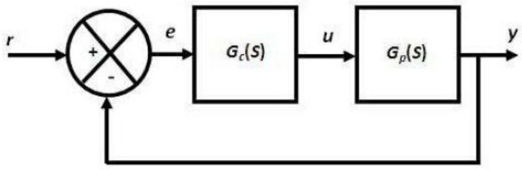

Fig 2.1: Structure of the feed-back control systems

The desired closed-loop transfer function of the system with controller is

$H(s) =$
$diag\left[\left(1 +\right.\right.$
Gp11sGc11s−1Gp11sGc11s;1+Gp22sGc22s−1Gp22sGc22s;….;1+GpnnsGcnns−1GpnnsGcnns

…………(4)

Now equation 4 can be written as

$H(s) =$
$diag[(G_{p11}^{-1}(s)G_{c11}^{-1}(s) + 1)^{-1}; (G_{p22}^{-1}(s)G_{c22}^{-1}(s) +$
1−1;….;Gpnn−1sGcnn−1s+1−1]

…….(5)

G_c is designed for H(s) to achieve a diagonal dominance for all frequencies [28].The inverse of the Eq.(5) can be approximated in order to H(s) diagonally dominance for all frequencies From Eq. 5, it can be written as

$$H(s)^{-1} = diag\left[\left(G_p^{-1}(s)G_c^{-1}(s) + I\right)^{-1}\right]^{-1}$$

…..(6)

Which is approximated as follows,

$$H(s)^{-1} \cong diag\left[\left(G_p^{-1}(s)G_c^{-1}(s) + I\right)^{-1}\right]^{-1}$$

…..(7)

The Eq.7, can be written in terms of decentralized controller as

$$G_c(s) = diag\left(G_p^{-1}(s)\right)(H^{-1}(s) - I)^{-1}$$

…….(8)

The controller $G_C(s)$ in Eq.8 includes two parts, that is, $diag(G_P^{-1}(s))$ and $(H^{-1}(s) - I)^{-1}$. The first part is

$$diag\left[G_p^{-1}(s)\right] = diag\left(\frac{adj\ G_p(s)}{|G_p(s)|}\right) = diag\left(\frac{G_p^{ii}(s)}{|G_p(s)|}\right)$$

…….(9)

Where , |Gp(s)| and adj(Gp(s)) denote determinant and adjoint of Gp(s) respectively.

Frequency dependent relative gain array of diagonal element of Gp(s) is calculated As

$A_{ii}(s) = g_{ii}(s)e^{-t_{ii}s}\frac{G_p^{ii}(s)}{|G_p(s)|}$ …….(10)

From eq. 9 and 10

$diag[G_p^{-1}(s)] = diag\left[\frac{A_{ii}(s)}{g_{ii}(s)e^{-t_{ii}s}}\right]$ ……(11)

Thus we will get

$(H^{-1}(s) - I)^{-1} = diag\left(\frac{h_{ii}(s)}{1-h_{ii}(s)}\right)$ ……(12)

Where, $h_{ii}(s)$ is the diagonal element of $H(s)$ and correspond to the closed loop transfer function of each(ii) loop.

$G_c(s) = diag(G_{cii}(s)) = diag\left[A_{ii}(s)[g_{ii}(s)e^{-t_{ii}s}]^{-1}\frac{h_{ii}(s)}{1-h_{ii}(s)}\right]$ ……(13)

2.2 Design of Controller

In internal model control theory [29], with assumption that the A is stable and causal, the closed-loop transfer function of the ith loop is

$h_{ii}(s) = \frac{e^{-t_{ii}s}}{(\lambda_i s+1)^{ri}}\prod_{k=1}^{q_i}\frac{Z_k - s}{Z_k^* + s}$ ……….(14)

where, Z_k, and Z_k^* denote the RHP zeros, and the corresponding complex conjugate of RHP zeros of the i^{th} diagonal element of the process transfer function matrix, respectively. q_i is the number of the RHP zeros. The term λ_i equivalent to the closed-loop time constant of λ_i loop, is an adjustable parameter and ri represents relative order of G_{pii}. From Eqs. 23 and 24, the multi-loop PID controller is

$G_{cii}(s) = \frac{A_{ii}(s)}{g_{ii}(s)e^{-t_{ii}s}}\frac{e^{-t_{ii}s}\prod_{k=1}^{q_i}\frac{Z_k-s}{Z_k^*+s}}{(\lambda_i s+1)^{ri} - e^{-t_{ii}s}\prod_{k=1}^{q_i}\frac{Z_k-s}{Z_k^*+s}}$ …………(15)

The above Eq. 3.25, can be written as

$G_{cii}(s) = s^{-1}P_{ii}(s)$ ……..(16)

where,

$$P_{ii}(s) = s\frac{A_{ii}(s)}{g_{ii}(s)}\frac{\prod_{k=1}^{q_i}\frac{Z_k - s}{Z_k^* + s}}{(\lambda_i s + 1)^{ri} - e^{-t_{ii}s}\prod_{k=1}^{q_i}\frac{Z_k - s}{Z_k^* + s}}$$

The non-minimum phase portion of gii(s) can be canceled with right-hand zeros of zk, hence the resulting controller has no problem of stability and causality. The controller resulted from Eq. 26, does not have standard PID form. The rational Maclaurin series expansion based approach can be used to approximate the non-PID controller into standard PID controller as

$G_{cii}(s) = \frac{1}{s}\left[P_{ii}(0) + sP_{ii}'(0) + \frac{s^2P_{ii}''(0)}{2}\right]$ …………..(17)

The standard form of the PID controller is

$G_{cii}(s) = \frac{1}{s}\left[k_{i,ii} + sk_{p,ii} + s^2k_{d,ii}\right]$ …………..(18)

The parameters of the multi-loop decentralized controllers can be obtained by comparing Eqs. 3.27 and 3.28 as

$k_{p,ii} = P_{ii}'(0);$

$k_{i,ii} = P_{ii}(0).$ (19)

and the derivative gain is obtained as

$$k_{d,ii} = \begin{cases} \left|\frac{P_{ii}''(0)}{2}\right| & P_{ii}'(0) \geq 0 \\ -\left|\frac{P_{ii}''(0)}{2}\right| & P_{ii}'(0) < 0 \end{cases}$$ …………..(20)

PID design procedure:

1. Select the desired closed-loop time constant λ_i of the i^{th} loop.
2. Obtain the relative gain array using Eq.
3. Select the appropriate q_i based on the non-minimum phase portion of $g_{ii}(s)$.
4. Select the relative order of numerator and denominator r_i.
5. Obtain the rational Maclaurin series expansion coefficients $P_{ii}(0)$, $P_{ii}'(0)$ and $P_{ii}''(0)$
6. Finally, obtain the tuned parameters of the PID for the i^{th} loop using Eqs. 19 and 20.

III. SIMULATION AND EXAMPLES

To show the applicability of the proposed algorithm two simulation examples are included. Mathworks MATLAB 7.1 is used to perform the simulation of the systems. The controller designed by proposed algorithm are compared with prevalent tuning methods given by Luyben [22],Wang et al.'s [32], Chien et al. [34],Qiang et al.[35] and Vu-Lee [33].

Example 3.1

The transfer function matrix of the Wood-Berry distillation column plant is given by

$$G_p(s) = \begin{bmatrix} \frac{12.8e^{-s}}{16.7s+1} & \frac{-18.9e^{-s}}{21.0s+1} \\ \frac{6.6e^{-7s}}{10.9s+1} & \frac{-19.4e^{-s}}{14.4s+1} \end{bmatrix}$$ …….(3.1)

With the detuning parameter $\lambda_1 = 1\ and\ \lambda_2 = 7$, the resulting $G_c(s)$ by proposed method is

$$G_c(s) = \begin{bmatrix} 0.79 + \frac{0.079}{s} + 0.36s & 0 \\ 0 & -0.083 - \frac{0.0104}{s} - 0.13s \end{bmatrix}$$ (3.2)

Wang auto-tuning method gives the controller as

$$G_{cWang}(s) = \begin{bmatrix} 0.216 + \frac{0.076}{s} + 0.017s & 0 \\ 0 & -0.068 - \frac{0.019}{s} - 0.064s \end{bmatrix} \quad .....(3.3)$$

The BLT method of Luyben gives

$$G_{cBLT}(s) = \begin{bmatrix} 0.375 + \frac{0.0452}{s} & 0 \\ 0 & -0.075 - \frac{0.0032}{s} \end{bmatrix} \quad ......(3.4)$$

The controller given by Chien is

$$G_{cChien}(s) = \begin{bmatrix} 0.881 + \frac{0.2294}{s} + 0.3841s & 0 \\ 0 & -0.136 - \frac{0.0165}{s} - 0.1673s \end{bmatrix} \quad (3.5)$$

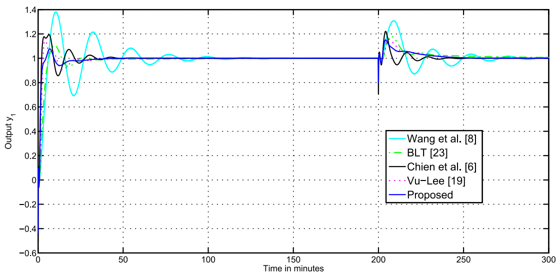

Fig.3.1 First output response for example 3.1

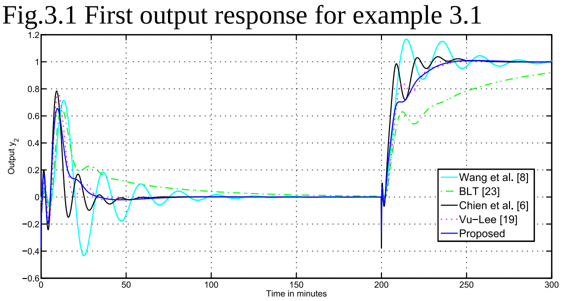

Fig.3.2 Second output response for example 3.1

The unit step at time t=0 minutes for the first set-point and unit step at time t=200 minutes for second set-point are applied. The output y_1 and y_2 in the figure. It is observed that the proposed controller has better performance as compared to others with less interaction. The output achieved by the proposed controller is with less overshoot and shorter setting time.

Example 3.2

Consider a industrial scale polymerization reactor presented in [34].The transfer matrix of the reactor is

$$G_P(S) = \begin{bmatrix} \frac{22.89e^{-0.2s}}{4.572s+1} & \frac{11.64e^{-0.4s}}{1.807s+1} \\ \frac{4.689e^{-0.2s}}{2.174s+1} & \frac{5.8e^{-0.4s}}{1.801s+1} \end{bmatrix} \quad .... (3.6)$$

With the detuning parameter $\lambda_1 = 0.09$ and $\lambda_2 = 0.69$, the resulting $G_c(s)$ by proposed method is

$$G_c(s) = \begin{bmatrix} 0.4217 + \frac{0.11}{s} + 0.097s & 0 \\ 0 & 0.13 + \frac{0.11}{s} + 0.094s \end{bmatrix}$$

...............(3.7)

The full structure of the PI controller withQiang et al.'s method [35] is

$$G_{cQiang}(s) = \begin{bmatrix} 0.06861 + \frac{0.3137}{s} & 0.1013 + \frac{0.2202}{s} \\ -0.021 - \frac{0.037}{s} & 0.1521 + \frac{0.2439}{s} \end{bmatrix} (3.8)$$

The BLT method of Luyben [22] gives,

$$G_{cBLT}(s) = \begin{bmatrix} 0.093 + \frac{0.21}{s} & 0 \\ 0 & 0.04235 + \frac{0.18}{s} \end{bmatrix} ....(3.9)$$

The controller given by Chien et al. [34] is

$$G_{cChien}(s) = \begin{bmatrix} 0.1852 + \frac{0.263}{s} & 0 \\ 0 & 0.092 + \frac{0.0163}{s} \end{bmatrix} ..(3.10)$$

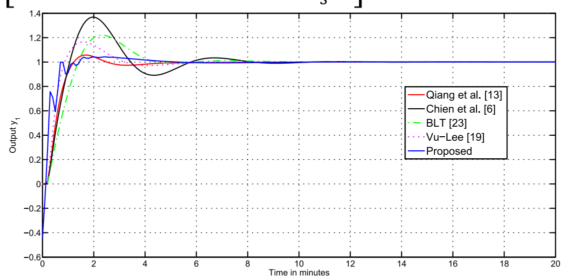

Fig.3.3 First output response to a unit step in the first input for example 3.2

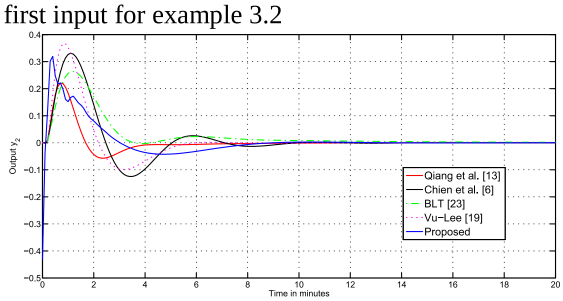

Fig.3.4 Second output response to a unit step in the first input for example 3.2

Thus output responses to a unit step in the first input are shown in Figs.3.3 and 3.4,while the output responses to a unit step in the second input are shown in Figs. 3.5-3.6.

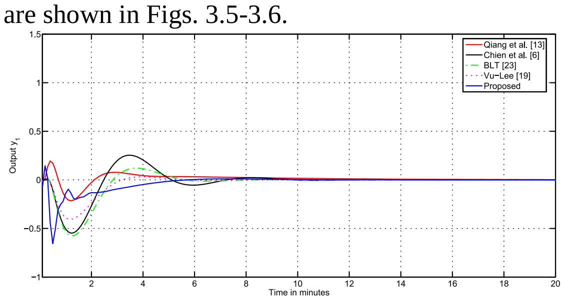

Fig.3.5 First output response to a unit step in the second input for example 3.2

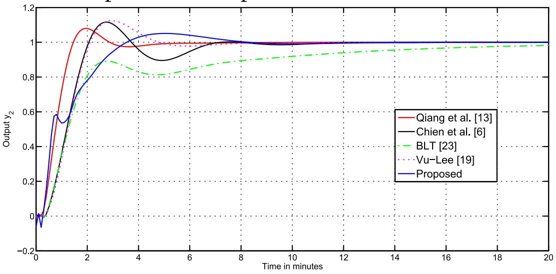

Fig.3.6 Second output response to a unit step in the second input for example 3.2

It can be seen from Figure 3.3-3.6 that the recovery to steady state point is fast while others are slow.

IV. CONCLUSION

A decentralized PID controller for MIMO processes is proposed which consists of diagonal

Controllers obtained by applying direct synthesis approach. The method uses Maclaurin series expansion which is simple, straightforward, and the well tuned parameters of the decentralized PID controllers are achieved for various processes. Two simulation examples are included to show the effectiveness of the proposed controller. The proposed algorithm not requires tedious work of decomposing multi-loop systems into single loops and design of the controller is straightforward with much simplicity. The proposed algorithm is tested for two input two output systems but can be extended for higher order multi-dimensional processes having complex dynamics and considerably multiple time delays. The proposed method is tested for two input two output systems and the performance seems to be comparable with existing available methods.

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