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Using Monovariable PID Controllers Tuned with Genetic Algorithms for Controlling a Multivariable Process

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Abstract

One advanced PID controller tuning method is using Genetic Algorithms. This tuning method is an optimization one that is based on the optimization of a cost function such Integral of Absolute magnitude Error (IAE), Integral of the Squared Error (ISE), Mean of the Squared Error (MSE) or Integral of Time multiplied by Absolute Error (ITAE). Genetic Algorithms use genetic operations like selection, crossover and mutation in order to search the potential solution of a problem starting for an initial random solution. The purpose of this paper is to design and implement a control system for a 2X2 multivariable process using two monovariable PID controllers tuned with Genetic Algorithms. The multivariable process dynamics and standard decoupling were studied in author's previous published works.

Key words: *PID controller design, PID controller tuning methods, Genetic Algorithms tuning method.*

Introduction

The PID algorithm is the most used type of control strategy, more than 95% of the control loops being of PID form. The PID controllers can be found in any area where control action is used as stand-alone systems, as a part of a distributed control system or as the lowest level of some advanced control strategies, such model predictive or internal model control [12].

Due to the PID controller widespread use, many tuning methods were developed in order to obtain better performance for different processes. There are two main categories of PID tuning methods, namely: classical methods (which give the values of the tuning parameters using formulas based on some process model parameters or on some values of the tuning parameters that bring the process to its limit of stability) and optimization methods (such Differential Evolution, Genetic Algorithms or Neural Networks techniques) [1].

Using Genetic Algorithms involves the following steps: generate the initial population consisting of different individuals who are possible solutions of the problem, evaluate the individuals based on an objective function, give the better ones a bigger chance to generate other individuals (solutions). This mechanism of generating other individuals is named reproduction and consists of three phases: selection, crossover and mutation [1].

Due to this mechanism, using Genetic Algorithms in order to obtain the PID controller tuning parameters, will give the optimum solution [1, 7, 8, 9, 10].

The objective of this paper is to use Genetic Algorithms (GA) method in order to find the tuning parameter values of two PID controllers that will be used in order to control the two outputs of a 2x2 multivariable process. In order to easily design the control structure, a 2x2 standard decoupler was designed taking into account the process dynamics [2] and the results were published in [4].

Multivariable Process Dynamics and Decoupling

The multivariable process represented in fig.1 and presented in [2, 3, 4] consists of two chambers, close one to each other, with one bulb each. The process input variables (U1 and U2) are the two voltages that can control the degree of the bulbs' light and the two output variables (Y1 and Y2) are the two chamber's temperatures. If we want to increase the temperature in one chamber, we will increase the voltage and the temperature will increase. Because of the small distance between the two chambers, the temperature in the other chamber will also increase [2].

The process is a 2x2 multivariable one, having four I-O channels. The dynamics on each process channel can be described by four models (G_{m11}, G_{m21}, G_{m12} and G_{m22}) (fig.1).

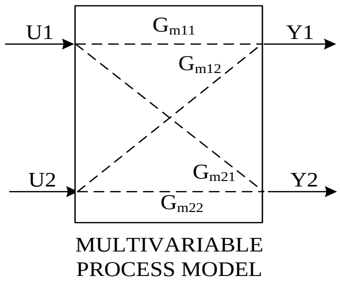

Fig. 1. Multivariable 2X2 process model block diagram: U1 and U2 – process inputs, Y1 and Y2 – process outputs, G_{m11} - the transfer function for U1-Y1 process channel, G_{m21} - the transfer function for U1-Y2 process channel, G_{m12} - the transfer function for U2-Y1 process channel and G_{m22} - the transfer function for U2-Y2 process channel [2].

Using simulation data the process model is described by a reunion of four first order transfer functions, one for each I-O channel [2]:

$$G_m(s) = \begin{bmatrix} G_{m11}(s) & G_{12}(s) \\ G_{m21}(s) & G_{m22}(s) \end{bmatrix} = \begin{bmatrix} \frac{k_{11}}{T_{11}\cdot s+1} & \frac{k_{12}}{T_{12}\cdot s+1} \\ \frac{k_{21}}{T_{21}\cdot s+1} & \frac{k_{22}}{T_{22}\cdot s+1} \end{bmatrix}, \quad (1)$$

where G_{m11} is the transfer function for U1-Y1 process channel, G_{m21} is the transfer function for U1-Y2 process channel, G_{m12} is the transfer function for U2-Y1 process channel and G_{m22} is the transfer function for U2-Y2 process channel [2].

From the data, the process model has the following form [2]:

$$G_m(s) == \begin{bmatrix} \frac{3.2}{6.7\cdot s+1} & \frac{0.7}{19.4\cdot s+1} \\ \frac{0.5}{15.3\cdot s+1} & \frac{2.7}{6.1\cdot s+1} \end{bmatrix}, \quad (2)$$

In order to design the control structure, the process I-O natural cross-interactions must be reduced or eliminated [6]. To do this a 2x2 structure, named decoupler was designed (see fig. 2) [3, 4].

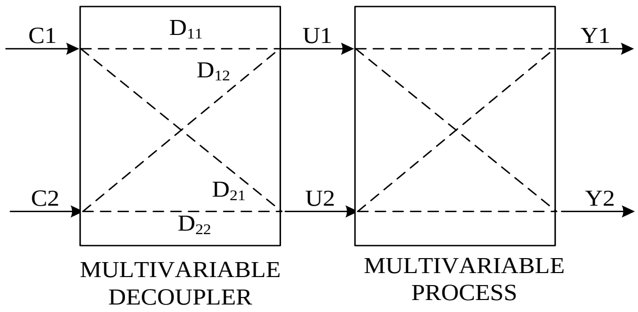

Fig. 2. Decoupled process block diagram: C1 and C2 – decoupler inputs, U1 and U2 – decoupler outputs/process inputs, Y1 and Y2 – process outputs.

There are two ways of designing the decoupler, using a process dedicated form or a standard form. The case of the dedicated decoupler was tested in [3] and the standard one in [4].

The conclusion was that much easier is to consider the second way, the standard decoupler variant.

The standard decoupler for the considered process (1) has the form [4]:

$$D(s) = \begin{bmatrix} D_{11}(s) & D_{12}(s) \\ D_{21}(s) & D_{22}(s) \end{bmatrix} = \begin{bmatrix} 1 & \dfrac{k_{D12}}{T_{D12} \cdot s + 1} \\ \dfrac{k_{D21}}{T_{D21} \cdot s + 1} & 1 \end{bmatrix}, \tag{3}$$

which for (2) becomes [4]:

$$D(s) = \begin{bmatrix} 1 & D_{12}(s) \\ D_{21}(s) & 1 \end{bmatrix} = \begin{bmatrix} 1 & \dfrac{-0.19}{9.2 \cdot s + 1} \\ \dfrac{-0.22}{12.7 \cdot s + 1} & 1 \end{bmatrix}. \tag{4}$$

The behavior of the multivariable process with decoupling (fig. 2) was investigated further in Figures 3 and 4, to step changes in the two inputs C1 and C2 [4].

As we can observe from Figures 3 and 4, we can consider that the obtained decoupled process behaves like two monovariable processes and in order to control two monovariable PID controllers can be used [4].

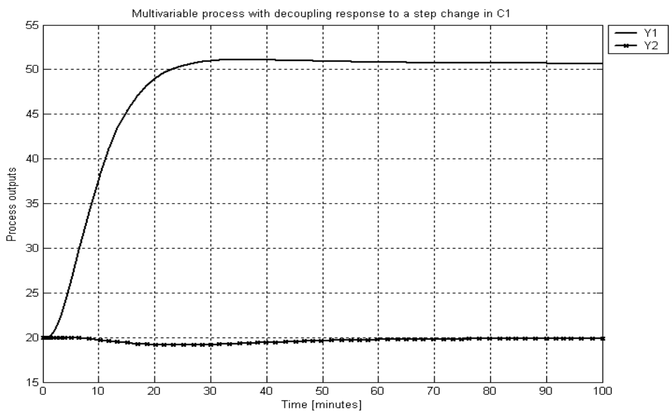

Fig.3. Decoupled process response (Y1 and Y2 [°C]) to a 10% step change in C1 [4].

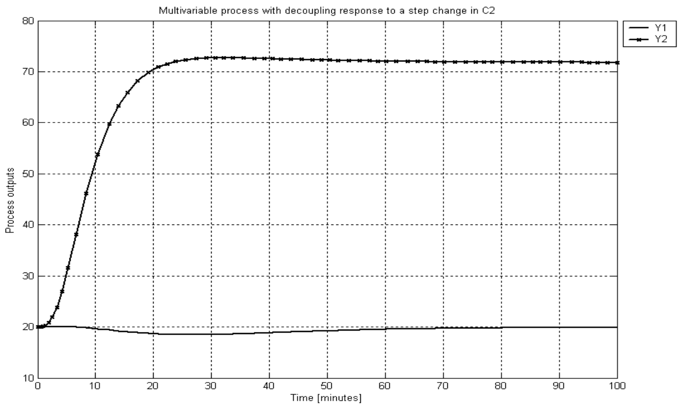

Fig.4. Multivariable process with decoupling response (Y1 and Y2 [°C]) to a 10% step change in C2 [4].

PID Controllers Design and Tuning

The proposed control system is represented in Figure 5.

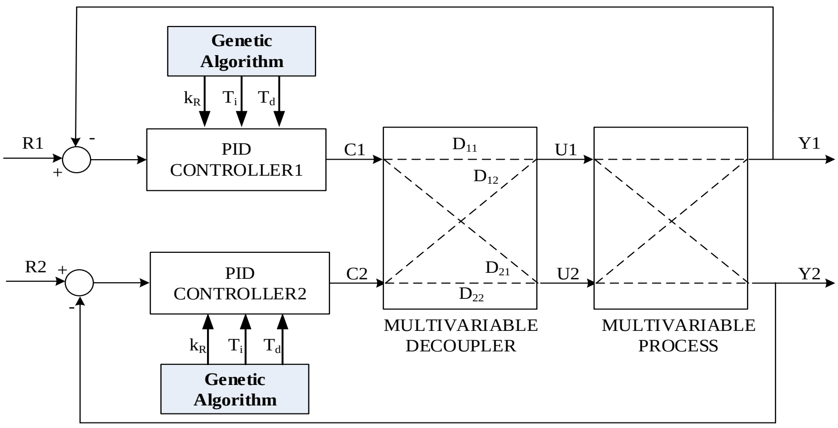

Fig. 5. The proposed control system block diagram: R1 and R2 – controller setpoints [°C], C1 and C2 – controller outputs/decoupler inputs [%], U1 and U2 – decoupler outputs/process inputs [%], Y1 and Y2 – process outputs [°C], k_R - controller gain; T_i - integral time constant and T_d is the derivative time constant.

The PID control algorithm has the time domain expression [5]:

$$c(t) = c_0(t) + k_R \cdot (e(t) + \frac{1}{T_i}\int_0^t e dt + T_d \frac{de}{dt}), \tag{5}$$

where $c_0(t)$ is the initial control value, $e(t)$ - error value, k_R - controller gain; T_i - integral time constant and T_d is the derivative time constant.

The PID controller transfer function has the expression

$$G_{PID}(s) = k_R \cdot (1 + \frac{1}{T_i \cdot s} + T_d \cdot s). \tag{6}$$

Because the derivative term is improper the PID controller transfer function will be considered as follows [1]:

$$G_{PID}(s) = k_R \cdot (1 + \frac{1}{T_i \cdot s} + \frac{T_d \cdot s}{\alpha \cdot T_d \cdot s + 1}), \tag{7}$$

where α is a weight constant having the value equal to 0.01, so that the lead derivative term to have a small influence, and the controller to be semiproper.

Genetic Algorithms (GA) tuning method block diagram is presented in fig. 6 [1].

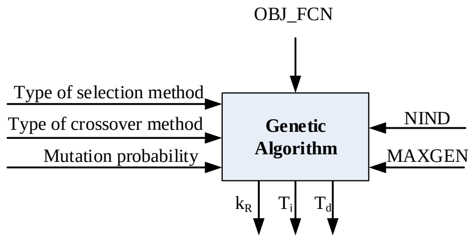

Fig. 6. Genetic Algorithms tuning method block diagram: OBJ_FCN is the objective function, MAXGEN – MAXimum number of GENerations, NIND – Number of INDividuals, k_R – controller gain, T_i – integral time constant, T_d – derivative time constant [1].

The GA has as input variables:

- the Objective Function (OBJ_FCN), which can be a mix between the control system Transient Time (T_{tr}) and the output Overshoot (OV);
- the type of selection method, that can be Roulette Wheel Selection (RWS), Stochastic Universal Sampling (SUS) or Tournament Selection (TS);
- the type of crossover method, that can be Single Point Crossover (SP), Two Point Crossover (TP) OR Multi Point Crossover (MP);
- the Mutation Probability (M_{PROB}); A probability of 0% means that the new individuals will be exact replicas of their parents and a probability of 100% means that the new individuals will be completely different from their parents;
- the maximum number of generations, MAXGEN;
- the number of individuals, NIND. Usually is used a number of 20-100 individuals.

The GA has as output variables the PID controller tuning parameters values:

- k_R - controller gain;
- T_i - integral time constant;
- T_d - derivative time constant.

In order to use GA tuning method, an initial solution must be generated. If this initial solution is a random one, can be some problems in finding the optimum solution. Because of this problem, the initial solution will be considered as the values of the three tuning parameters found using Ziegler-Nichols (Z-N) PID tuning method.

Accordingly Z-N, the PID tuning parameters are computed as follows [11]:

$$k_R = 0.6 \cdot k_C,\ T_i = 0.5 \cdot P_C,\ T_d = 0.13 \cdot P_C, \tag{8}$$

where k_C is the critical gain and P_C is the oscillations period of the controller output for the critical gain.

In order to find the two parameters (k_c and P_c) the following steps are required:

- set the process under proportional control, with a small controller gain (k_R), having $T_i = \infty$ and $T_d = 0$;
- increase the gain (k_R) until the loop starts oscillating for a setpoint step change, as in Fig. 7A.

- increase more the controller gain (k_R) until the loop oscillates with constant amplitude, as in Figure 7C;
- save this value of the controller gain as the critical gain ($k_R = k_C$);
- record the oscillations period of the controller output (P_C) as in Figure 7C;
- compute the controller tuning parameters according to formulas (8) based on k_C and P_C values.

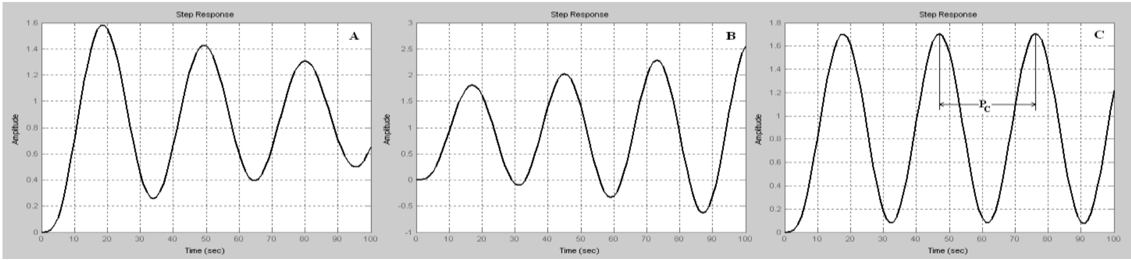

Fig. 7. The control system closed-loop response for a setpoint step change, for different values of controller gain in order to obtain de critical gain (k_C) and oscillation period (P_C): A – the controller gain value is not enough in order to obtain oscillations with constant amplitude and must be increased; B – the controller gain value is too large because the oscillations amplitude increase, the controller gain must be decreased; C – the controller gain value is the critical one (k_C) because the oscillations have constant amplitude, the oscillation period is P_C.

In Figure 8 it is presented the process output Y1 trend, for a step change in R1 (fig. 5), from 20 to 45°C, having k_{C1}=2.6, T_{i1}=9999 min and T_{d1}=0 min.

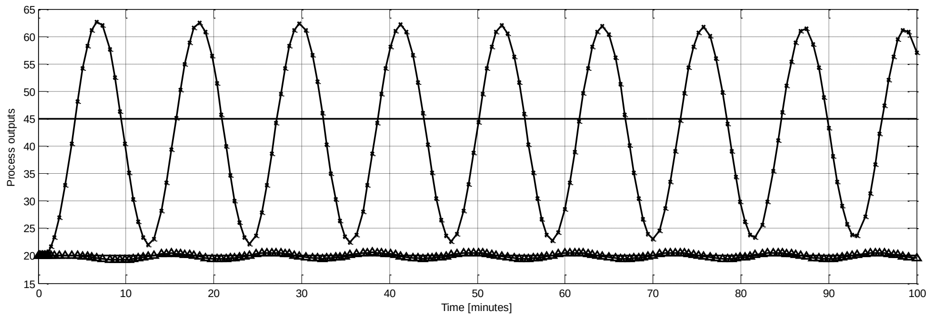

Fig.8. The process output Y1 trend to a 25°C step change in R1, from 20 to 45°C, having k_{C1}=2.6, T_{i1}=9999 min and T_{d1}=0 min.

In Figure 9 it is presented the process output Y2 trend, for a step change in R2 (fig. 5), from 20 to 35°C, having k_{C1}=2.27, T_{i1}=9999 min and T_{d1}=0 min.

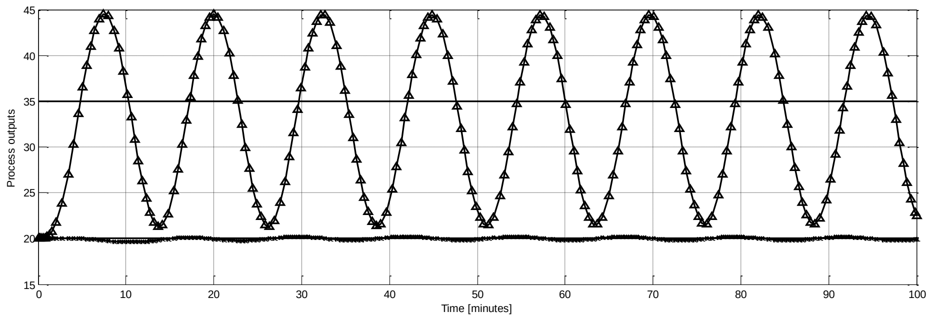

Fig.9. The process output Y2 trend to a 15°C step change in R2, from 20 to 35°C, having k_{C1}=2.27, T_{i1}=9999 min and T_{d1}=0 min.

As we can see from Figures 8 and 9, the k_R values for the two PID controllers are the critical ones, the process outputs oscillate with a constant amplitude.

Using (8) the PID tuning parameter values for the two controllers are:

$$k_{R1} = 0.6 \cdot 2.6 = 1.56,\ T_{i1} = 0.5 \cdot 12\,\text{min} = 6\,\text{min},\ T_{d1} = 0.13 \cdot 12\,\text{min} = 1.56\,\text{min}, \quad (9)$$

and

$$k_{R2} = 0.6 \cdot 2.27 = 1.362,\ T_{i2} = 0.5 \cdot 13 = 6.5\,\text{min},\ T_{d2} = 0.13 \cdot 13\,\text{min} = 1.69\,\text{min}. \quad (10)$$

These values of the PID tuning parameters will be considered as initial solutions for GA.

Using the results from [1] the values for the input variables of the GA are:

The considered objective function is:

$$OBJ\_FCN(k_R, T_i, T_d) = \lambda_T \cdot T_{tr} + \lambda_{OV} \cdot OV, \quad (11)$$

where λ_T is the weight of T_{tr} and λ_{OV} is the weight of OV. The sum of all weights must be one.

The Transient Time (T_{tr}) is considered as the time in which the output has reached 98% from its steady state value. In the practical applications, the control system T_{tr} is better to be as close as possible to the process T_{tr}, or even smaller.

The output overshoot, OV is computed as the difference between the maximum output value and the steady state value.

- the type of selection method: Stochastic Universal Sampling (SUS);
- the crossover technique: Single Point Crossover method;
- the mutation probability: M_{PROB} = 0.01%.
- the maximum number of generations: MAXGEN = 100;
- the number of individuals: NIND = 40.

Using the above GA I-O variable values, the initial values of the PID controller tuning parameters (9 and 10) and applying the GA tuning method for the considered model of the process, the values of the PID tuning parameters (k_R, T_i and T_d) for the two controllers (fig. 5) are:

$$k_{R1} = 0.58,\ T_{i1} = 12.1\,\text{min},\ T_{d1} = 2.3\,\text{min}, \quad (12)$$

and

$$k_{R2} = 0.9,\ T_{i2} = 14.5\,\text{min},\ T_{d2} = 3.1\,\text{min}. \quad (13)$$

Results

Further, the control system was investigated for step changes in the two controller's setpoints (fig. 5) for the obtained values of the PID tuning parameters, see fig. 10-14.

Considering the PID tuning parameter values obtained with Z-N we have the following trends, see Figures 10 and 11.

Considering the PID tuning parameter values obtained with GA, we have the following dynamic responses, see Figures 12 and 13.

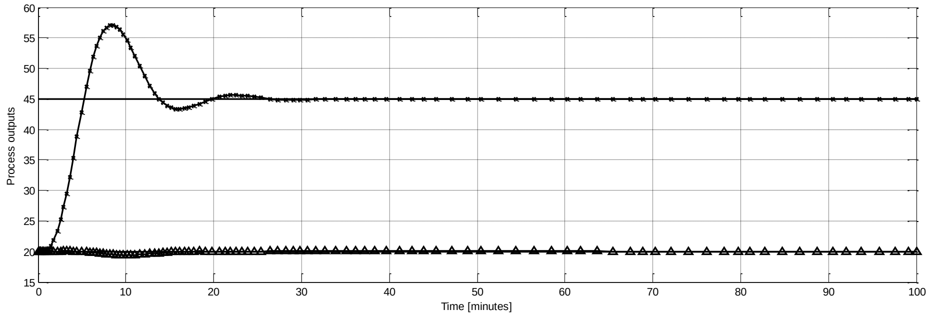

Fig.10. Control system response (Y1 and Y2 [°C]) to a 25°C step change in R1, from 20 to 45°C, having k_{R1}=1.56, T_{i1}=6 min and T_{d1}=1.56 min.

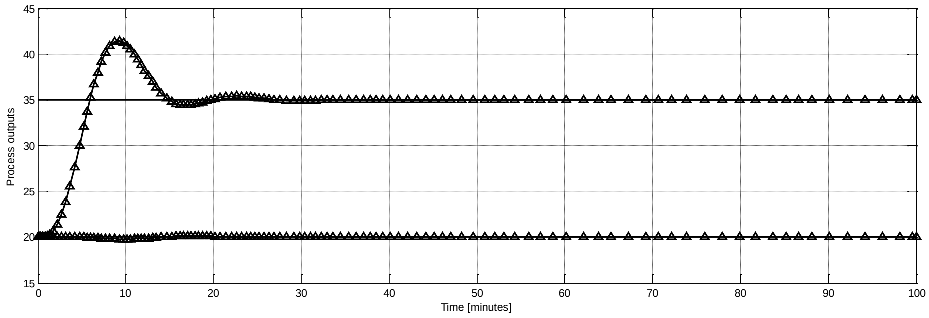

Fig.11. Control system response (Y1 and Y2 [°C]) to a 15°C step change in R2, from 20 to 35°C, having k_{R2}=1.362, T_{i2}=6.5 min and T_{d2}=1.69 min.

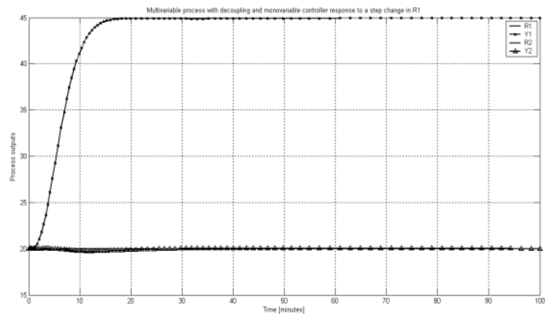

Fig.12. Control system response (Y1 and Y2 [°C]) to a 25°C step change in R1, from 20 to 45°C, having k_{R1}=0.58, T_{i1}=12.1 min and T_{d1}=2.3 min.

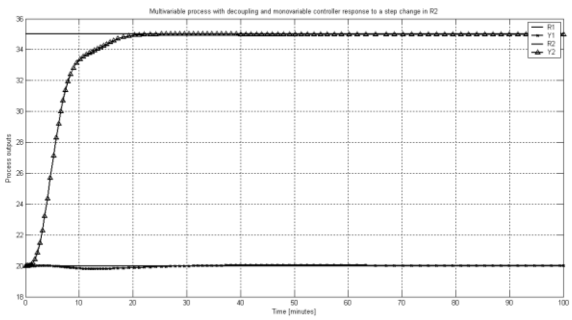

Fig.13. Control system response (Y1 and Y2 [°C]) to a 15°C step change in R2, from 20 to 35°C, having k_{R2}=0.9, T_{i2}=14.5 min and T_{d2}=3.1 min.

As we can observe from the above figures (fig. 10 - 13) when the setpoint for one chamber temperature is changed, the temperature for that chamber changes and the temperature from the other chamber remains approximately unchanged.

Also, if we consider the values of the PID tuning parameters obtained with Z-N method, we have a small transient time and output overshoot. In case of using the values of the PID tuning parameters obtained with GA method, we have the smallest transient time and no output overshoot.

In fig. 14 was considered the case when the setpoints, for the two chamber temperatures, are changed at once. As we can see the system works with good results.

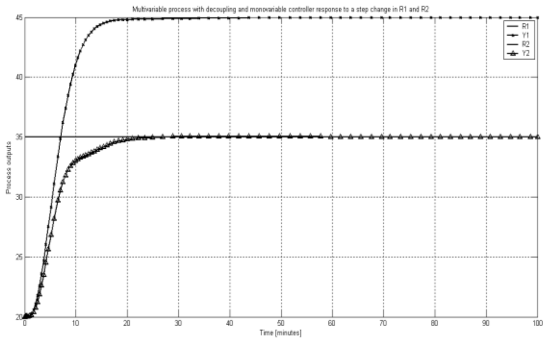

Fig.14. Control system response (Y1 and Y2 [°C]) to a 30°C step change in R1, from 20 to 50°C and to a 20°C step change in R2,from 20 to 40°C, having k_{R1}=0.58, T_{i1}=12.1 min, T_{d1}=2.3 min and k_{R2}=0.9 and T_{i2}=14.5 min, T_{d2}=3.1 min.

Conclusions

This paper objective was to use Genetic Algorithms (GA) method in order to find the tuning parameter values of two PID controllers used in order to control the two outputs of a 2x2 multivariable process. In order to easily design the control structure, the process I-O natural cross interactions were reduced using a 2x2 standard decoupler with a simple standard model (of first order) that is easy to design and implement.

In order to use the GA tuning method, the first step is to generate some initial solutions for the three PID tuning parameter values, from which the GA can start on finding the optimum solution according to the considered objective function.

These initial solutions were considered the values obtained with Ziegler-Nichols PID tuning method.

The optimal solution for the three tuning parameters is found in order to have the smallest transient time and no output overshoot, according to the considered objective function.

The proposed control structure was tested for validation considering the two controllers setpoint step changes, observing that the control system the best steady-state and dynamic performance.

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Utilizarea regulatoarelor monovariabile PID acordate cu algoritmi genetici pentru reglarea unui proces multivariabil

Rezumat

O metodă avansată de acordare a regulatorului PID este folosind algoritmii genetici. Această metodă de acordare este una de optimizare care se bazează pe extremizarea unei funcţii cost cum ar fi Integrala Erorii Absolute (IAE), Integrala Erorii Pătratice (ISE), Eroarea Pătratică Medie (MSE) sau Integrala Timpului înmulţit cu Eroare Absolută (ITAE). Algoritmii genetici utilizează operaţii specifice geneticii cum ar fi selecţia, încrucişarea şi mutaţia, în scopul căutării potenţialei soluţii a unei probleme pornind de la o soluţie iniţială aleatoare. Scopul acestei lucrări este de a proiecta şi implementa un sistem de reglare pentru un proces multivariabil 2X2 cu ajutorul a două regulatoare monovariable PID acordate cu algoritmi genetici. Dinamica procesului multivariabil şi decuplarea standard a acestuia au fost studiate în lucrări publicate anterior de către autor.