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Decentralized PID Controller Design for a MIMO Evaporator Based on Colonial Competitive Algorithm

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Abstract: Recently, Colonial Competitive Algorithm (CCA) has proven its superior capabilities, such as faster convergence and better global minimum achievement in optimization problems. In this paper, CCA is utilized to optimize the coefficients of a decentralized PID controller for a MIMO evaporator system. The optimization criterion is considered as the Integral Absolute Error (IAE) to minimize the tracking error. As the first step, the evaporator's three input-three output transfer matrix is identified using measured dataset based on the prediction error model method. In order to design decentralize controllers, input-output pairing is performed based on the relative Gain Array method. Decentralized PID controllers are then designed using Ziegler-Nichols, Genetic Algorithm, and the proposed CCA techniques. The simulation results verify the superiority of CCA to the Ziegler-Nichols and Genetic Algorithm tuning techniques for decentralized PID controllers.

1. INTRODUCTION

Proportional-integral-derivative (PID) controller has been the most popular control loop feedback mechanism since 1950s, and has been extensively used in controlling industrial plants. In addition to its capabilities, PID can be implemented easily in industrial control processes. PID controller tries to correct the error between the measured outputs and desired outputs of the process so that transient and steady state responses are improved as much as possible. Although it is used widely, PID tuning is still an area of research in realm of both academic and industrial control engineering, while different methods have been proposed (Bao *et al.*, 1999 : Chidambaram & Sree, 2003 : Lee *et al.*, 2004 : Wang *et al.*, 1998). Among them, Ziegler-Nichols tuning method is considered to be a very popular approach (Ziegler and Nichols, 1942). One the other hand, controlling Multi Input Multi Output systems is not straight forward due to the coupling and interactions between channels. In last several decades, designing controllers for MIMO systems has attracted a lot of research interests (Christen *et al.*, 1997 : Roffel *et al.*, 2000 : Su *et al.*, 2007). Among the proposed MIMO controllers, decentralized PID controllers have been deployed extensively due to their less complexity, high performance and easy implementation (Halevi *et al.,* 1997 : Su *et al.*, 2007 : Xiong *et al.,* 2007).

In this paper, Colonial Competitive Algorithm (CCA) is used to tune parameters of a decentralized PID controller for a MIMO evaporator. First, the model of the evaporator is identified based on measured data. The plant is a four-stage three input- three output industrial evaporator which is used to reduce the water content of products like milk. The plant inputs are feed flow, vapour flow to the first evaporator stage, and cooling water flow. The three outputs of the evaporator are the dry matter content, the flow, and the temperature of the out coming product. Measured Input/Output data used for identification of the plant parameters is taken from (URL1). Prediction error model (Nelles, 2001) is used to identify the transfer matrix parameters of the plant. In order to design decentralized controller, the appropriate pairings among inputs and outputs are chosen to weaken the interactions between channels. Then a decentralized PID controller is designed using Ziegler-Nichols method for the identified model. The determined PID coefficients are used as the initial estimate of two evolutionary optimization algorithms, Genetic Algorithm (GA) and Colonial Competitive Algorithm (CCA), (Atashpaz-Gargari & Lucas 2007 a, b : Biabangard-Oskouyi *et al.*, 2007). CCA is a novel global search strategy that uses the socio-political competition among empires as a source of inspiration. Like other evolutionary ones that start with an initial population, CCA begins with initial empires. Any individual of an empire is a country. There are two types of countries; colony and imperialist state that collectively form empires. Imperialistic competition among these empires forms the basis of the CCA. During this competition, weak empires collapse and powerful ones take possession of their colonies. Imperialistic competition converge to a state in which there exist only one empire and its colonies are in the same position and have the same cost as the imperialist. The simulation results show the superiority of the optimized decentralized PID controller using CCA, to the Ziegler-Nichols and GA approaches.

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2. MODELING AND IDENTIFICATION OF THE EVAPORATOR SYSTEM

In order to model the evaporator plant, Matrix Polynomial Model (Nelles, 2001) is utilized. The general form of the three input- three output MIMO transfer matrix is as follows:

$$\begin{bmatrix} y_1(s) \\ y_2(s) \\ y_3(s) \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) & G_{13}(s) \\ G_{21}(s) & G_{22}(s) & G_{23}(s) \\ G_{31}(s) & G_{32}(s) & G_{33}(s) \end{bmatrix} \times \begin{bmatrix} u_1(s) \\ u_2(s) \\ u_3(s) \end{bmatrix}$$

where

$$G_{ij}(s) = \frac{K_{ij} e^{-T_{dij} s}}{1 + a_{ij} s + b_{ij} s^2} \qquad i, j = 1,2,3$$

The transfer matrix parameters, K_{ij}, T_{dij}, a_{ij}, b_{ij}, are estimated using generalized auto-regressive exogenous ARX (GARX). estimation method (Nelles, 2001). For simplicity, each channel output is used with three inputs, i.e. the corresponding row of the transfer matrix, for identification. Measured Input/Output data used for identification of the plant parameters is taken from (URL1). The estimated parameters of the evaporator's plant model are summarized in Table 1.

Table 1. Estimated parameters of industrial evaporator

	K	T_d	a	b
G_{11}	-2.0039	1.1696	7.7385	38.1257
G_{12}	3.012	0	51.8718	134.0501
G_{13}	3.6631	0	25.0926	9.9768
G_{21}	2.0507	0	2.9782	13.4403
G_{22}	-0.7047	0	5.0090	4.4957
G_{23}	-0.7420	0.0439	73.1647	3.29×10^{-6}
G_{31}	0.4431	0	6.0349	48.9426
G_{32}	2.519	1.1629	117.3263	467.3812
G_{33}	-4.223	0	16.3252	66.1506

In order to verify the accuracy of the identified model, the mean square error (MSE) criterion is used as follows:

$$MSE_i = \frac{\sum_{j=1}^{N} (y_i^j - \hat{y}_i^j)^2}{N} \quad , i = 1,2,3 \qquad (1)$$

where N is the number of measured samples, which is 6305 in this paper, and y_i indicates the relevant output. Obtained MSEs for y_1,y_2 and y_3 are 0.1671, 0.2193 and 0.3023, respectively.

3. DECENTRALIZED PID CONTROLLER DESIGN

3.1. Input-Output Pairing

In Fig. 1 the multivariable control loop for the evaporator plant is shown. Furthermore, $\mathbf{Y}_d$,**Y**, **E**, **C**(s) and **P**(s) are defined as follows:

$$\mathbf{Y}_d = [y_{d1} \quad y_{d2} \quad y_{d3}]^T \quad , \quad \mathbf{Y} = [y_1 \quad y_2 \quad y_3]^T$$

$$\mathbf{C}(s) = \begin{bmatrix} c_{11}(s) & 0 & 0 \\ 0 & c_{22}(s) & 0 \\ 0 & 0 & c_{33}(s) \end{bmatrix}, \ \mathbf{P}(s) = \begin{bmatrix} p_{11}(s) & p_{12}(s) & p_{13}(s) \\ p_{21}(s) & p_{22}(s) & p_{23}(s) \\ p_{31}(s) & p_{32}(s) & p_{33}(s) \end{bmatrix}$$

$$\mathbf{E} = \mathbf{Y}_d - \mathbf{Y} = [e_{11} \quad e_{22} \quad e_{33}]^T$$

where $p_{ij}(s)$ is the transfer function between y_i and u_j and $c_{ii}(s)$, ($i, j \in \{1,2,\ldots,n\}$) , is represented by

$$c_{ii}(s) = K_{Pii} + K_{Iii} / s + K_{Dii} s$$

In which K_{pii} is the proportional, K_{Iii} is the integral and K_{Dii} is the derivative gains of the PID controller c_{ii}(s).

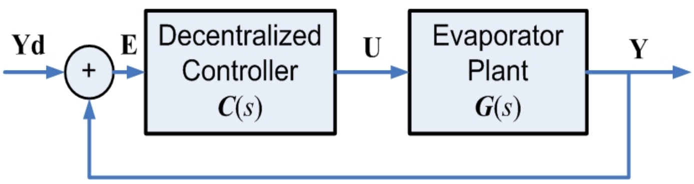

Fig. 1. Block diagram of a multivariable controlled process

In order to design the appropriate decentralized controller, proper pairing for plants' inputs and outputs should be performed to reduce channel interactions as much as possible. Relative Gain Array (RGA) at steady state, a common criterion in pairing selection (Hovd & Skogestad, 1993), is used as follows:

$$RGA = G(0) \otimes (G(0)^{-1})^T$$

where G(0) is the dc-gain of transfer matrix and ⊗ indicates element by element matrix product.

There are six possible pairings for the three input- three output evaporator plant model, identified in section 2. The corresponding RGA matrices for all possible pairings are as follows:

$$RGA_{1-2-3} = \begin{bmatrix} -0.27 & 0.71 & 0.56 \\ 1.27 & -0.13 & -0.13 \\ 0.01 & 0.42 & 0.56 \end{bmatrix} \quad RGA_{2-1-3} = \begin{bmatrix} 0.71 & -0.28 & 0.57 \\ -0.13 & 1.27 & -0.14 \\ 0.42 & 0.03 & 0.57 \end{bmatrix}$$

$$RGA_{2-3-1} = \begin{bmatrix} 0.71 & 0.57 & -0.28 \\ -0.13 & -0.14 & 1.28 \\ 0.43 & 0.57 & 0.01 \end{bmatrix} \quad RGA_{1-3-2} = \begin{bmatrix} -0.28 & 0.57 & 0.71 \\ 1.27 & -0.14 & -0.14 \\ 0.01 & 0.57 & 0.43 \end{bmatrix}$$

$$RGA_{3-1-2} = \begin{bmatrix} 0.57 & -0.28 & 0.71 \\ -0.14 & 1.28 & -0.14 \\ 0.57 & 0.01 & 0.43 \end{bmatrix} \quad RGA_{3-2-1} = \begin{bmatrix} 0.57 & 0.71 & -0.28 \\ -0.14 & -0.14 & 1.28 \\ 0.57 & 0.43 & 0.01 \end{bmatrix}$$

where $RGA_{i\text{-}j\text{-}k}$ is the relative gain array of the following pairing *i-j-k*.

$$\begin{bmatrix} y_1(s) \\ y_2(s) \\ y_3(s) \end{bmatrix} = \begin{bmatrix} G_{1i}(s) & G_{1j}(s) & G_{1k}(s) \\ G_{2i}(s) & G_{2j}(s) & G_{2k}(s) \\ G_{3i}(s) & G_{3j}(s) & G_{3k}(s) \end{bmatrix} \times \begin{bmatrix} u_i(s) \\ u_j(s) \\ u_k(s) \end{bmatrix}$$

Based on the obtained RGAs at steady state, it can be realized that the pairing *2-1-3* results in less couplings among channels comparing with other options.

Once the appropriate pairing option is selected, a diagonal PID controller is designed for the identified plant.

3.2. Tuning Diagonal PID Controller parameters

In designing PID controllers, the goal is to tune proper coefficients K_P, K_I and K_D so that the output has some desired characteristics, such as overshoot, rise time, settling time, and steady state error. This is usually achieved by optimization of some performance criterions. Two well known performance criterions are the integral squared error (ISE) and integral absolute error (IAE) of the tracking error.

In multivariable controller design, a major goal is to reduce the tacking error due to the interactions. So, the controller should be designed such that $y_i(t)$ track the desired ouput, $y_{di}(t)$, with minimum channel interactions. For this purpose, the IAE criteria is defined in the following form.

$$IAE \triangleq \sum_{i=1}^{n}\sum_{j=1}^{n} IAE_{ij} \triangleq \int_0^\infty \left(\sum_{i=1}^{n}\sum_{j=1}^{n} \left| e_{ij}(t) \right| \right) dt \tag{2}$$

where $|e_{ii}(t)|$ is the absolute tracking error due to the ith input, and $|e_{ij}(t)|$ is the absolute tracking error caused by the interaction effect from the jth input ($i \neq j$). The source of $|e_{ij}(t)|$ is the coupling problem. The aim is to design a controller to track the desired inputs with minimum interactions from other channels. For this purpose, Genetic Algorithm and Colonial Competitive Algorithm are used to tune the controller parameters by optimization of the proposed performance criteria.

CCA is a novel global heuristic search method that uses imperialism and imperialistic competition process as a source of inspiration. Fig. 2 shows the pseudo code for this algorithm. This algorithm starts with some initial countries. Some of the best countries are selected to be the *imperialist states* and all the other countries form the *colonies* of these imperialists. The colonies are divided among the mentioned imperialists based on their power. After dividing all colonies among imperialists and creating the initial empires, these colonies start moving toward their relevant imperialist state. This movement is a simple model of assimilation policy that was pursued by some imperialist states (Atashpaz-Gargari & Lucas 2007 a). Fig. 3 shows the movement of a colony towards the imperialist. In this movement, θ and *x* are random numbers with uniform distribution as illustrated in (3) and *d* is the distance between colony and the imperialist.

$$\begin{aligned} x &\sim U(0, \beta \times d) \\ \theta &\sim U(-\gamma, \gamma) \end{aligned} \tag{3}$$

where β and γ are arbitrary numbers that modify the area that colonies randomly search around the imperialist. In our implementation β and γ are 2 and 0.5 (rad), respectively.

The total power of an empire depends on both the power of the imperialist country and the power of its colonies. In this algorithm, this fact is modelled by defining the total power of an empire by the power of imperialist state plus a percentage of the mean power of its colonies. In imperialistic competition, all empires try to take possession of colonies of other empires and control them. This competition gradually brings about a decrease in the power of weak empires and an increase in the power of more powerful ones.

```
1)  Select some random points on the function
    and initialize the empires.
2)  Move the colonies toward their relevant
    imperialist (Assimilating).
3)  If there is a colony in an empire which
    has lower cost than that of imperialist,
    exchange the positions of that colony and
    the imperialist.
4)  Compute the total cost of all empires
    (Related to the power of both imperialist
    and its colonies).
5)  Pick the weakest colony (colonies) from
    the weakest empires and give it (them) to
    the empire that has the most likelihood to
    possess it (Imperialistic competition).
6)  Eliminate the powerless empires.
7)  If there is just one empire, stop, if not
    go to 2.
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Fig. 2. Pseudo code of the Colonial Competitive Algorithm

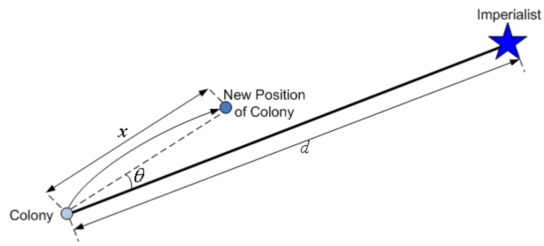

Fig. 3. Motion of colonies toward their relevant imperialist.

This competition is modelled by just picking some (usually one) of the weakest colonies of the weakest empires and making a competition among all empires to possess these (this) colonies. Fig. 4 shows a big picture of the modelled imperialistic competition. Based on their total power, in this competition, each of empires will have a likelihood of taking possession of the mentioned colonies. The more powerful an empire, the more likely it will possess these colonies. In other words these colonies will not be certainly possessed by the most powerful empires, but these empires will be more likely to possess them. Any empire that is not able to succeed in imperialist competition and can not increase its power (or at least prevent decreasing its power) will be eliminated.

The imperialistic competition will gradually result in an increase in the power of great empires and a decrease in the power of weaker ones. Weak empires will gradually loose their power and ultimately they will collapse.

The movement of colonies toward their relevant imperialists along with competition among empires and also collapse mechanism will hopefully cause all the countries to converge to a state in which there exist just one empire in the world and all the other countries are its colonies. In this ideal new

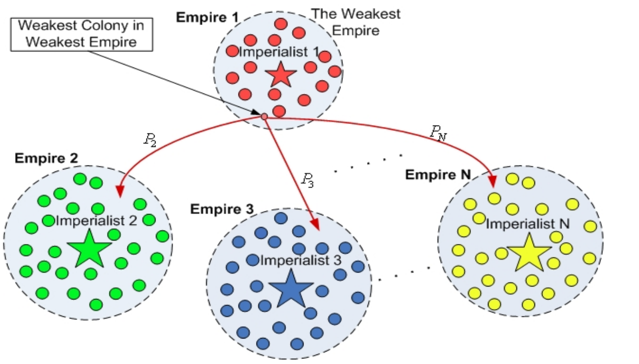

Fig. 4. Imperialistic competition: The more powerful an empire is, the more likely it will possess the weakest colony of weakest empire.

world colonies have the same position and power as the imperialist.

4. SIMULATION RESULTS

In this section, we design a multivariable decentralized PID controller for the evaporator plant, which was identified in section 2. The nine transfer functions in multivariable process have second-order dynamics and significant time delays. The control objective is tracking the control inputs y_{1d}=y_{2d}=y_{2d}=1 by outputs y_1, y_2 and y_3 and reduce the interactions as much as possible. First, the well known Ziegler-Nichols method was utilized to obtain the controller parameters:

$$c_{11}(s) = 9.6998 + 0.1217/s + 8.7174s$$

$$c_{22}(s) = 1.9151 + 0.3029/s + 1.3416s$$

$$c_{33}(s) = -2.1858 - 0.0923/s - 2.3449s$$

Then we use two evolutionary algorithms, GA and CCA, to tune the PID parameters, obtained in section 2. The task is a nine-dimensional optimization problem of determining the optimal coefficients [K_{P11} K_{I11} K_{D11} K_{P22} K_{I22} K_{D22} K_{P33} K_{I33} K_{D33}] to minimize the cost function (2). In CCA, initial number of countries is set to 100, 10 of which are chosen to form the initial empires. Also β and γ are set to 2 and 0.5 (*rad*), respectively. The maximum number of iterations in CCA is set to 350 but we reached the total IAE cost of 37.9875 in 174 iterations. This is because of the fact that, at iteration 174, imperialistic competition concluded to the state in which only one imperialist is alive, when the imperialistic competition stops and the algorithm converges to the optimal point. In simulations we excluded those controller parameters that seemed to produce large value of IAE. Besides, GA is also used to tune the parameters of the decentralized PID controller for the process. As for CCA, in GA the initial number of populations is set to 100 and selection and mutation rates are put 50% and 30 % respectively. The minimum cost of GA converged to its steady state value, 41.7556, at iteration about 350. It is worth mentioning that, to have a better convergence, the initial population in GA and initial countries in CCA are scattered over a hypercube centred on the controller coefficients obtained by the Ziegler-Nichols method.

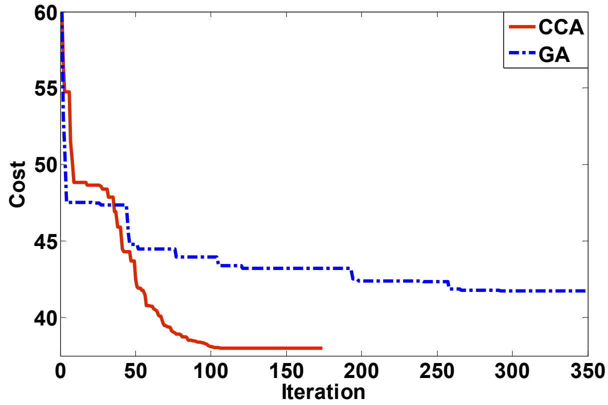

Fig. 5. Minimum cost of CCA and GA versus iteration.

Fig. 5 depicts the minimum costs of CCA and GA together versus iteration. Based on this figure, the IAE converges to 37.9875 with CCA, which is less than that of GA, 41.7556. It is noteworthy that the convergence rate of CCA is much better than that of GA. Parameters of PID controller and their relevant IAE cost obtained by CCA, GA and Ziegler-Nichols methods are demonstrated in tables 2 and 3, respectively. To make a better sense of the values in Table 3, the minimum IAE cost in each column is highlighted, having different colors for IAE_{ii} $(i \in \{1,2,3\})$ and IAE_{ij} $(i, j \in \{1,2,3\}, i \neq j)$.

Table 2. Parameters of PID controller obtained by Ziegler-Nichols method and tuned using CCA and GA.

	CCA	GA	Ziegler-Nicholes
K_{P11}	10.597	10.458	9.7
K_{I11}	0.085	0.122	0.122
K_{D11}	12	11.229	8.717
K_{P22}	12	11.375	1.955
K_{I22}	0.398	0.471	0.303
K_{D22}	12	5.462	1.342
K_{P33}	-4	-3.148	-2.186
K_{I33}	-0.149	-0.232	-0.092
K_{D33}	-4	-3.875	-2.345

According to Table 3, the controller obtained by GA has resulted in the least cost only for IAE_{12}. That is, comparing to CCA and Ziegler-Nichols methods, using controller obtained by GA, the first output is not significantly affected by the second input. Also considering IAE_{13}, the controller obtained by Ziegler-Nichols method, has better performance than CCA and GA. For all IAE costs other than IAE_{12} and IAE_{13}, the controller obtained by CCA has better performance.

Furthermore, considering the total cost IAE, the controller obtained by CCA has the best performance. Fig. 6 shows the response of controlled evaporator process to step inputs using decentralized PID controllers tuned by CCA, GA. To have a better view of different controllers' abilities in tracking, step inputs are applied with delays of 50, 400 and 600 seconds.

Table 3. Different parts of cost function IAE obtained by Ziegler-Nichols method and optimized by CCA and GA.

	CCA	GA	Ziegler Nicholes
IAE_{11}	8.435	8.631	9.034
IAE_{12}	5.542	5.328	5.551
IAE_{13}	7.1532	7.495	6.389
IAE_{21}	2.262	2.677	10.827
IAE_{22}	1.918	2.246	5.946
IAE_{23}	2.268	2.402	8.889
IAE_{31}	3.338	4.367	5.850
IAE_{32}	2.347	2.676	3.993
IAE_{33}	4.997	5.915	7.215
IAE	37.987	41.755	63.694

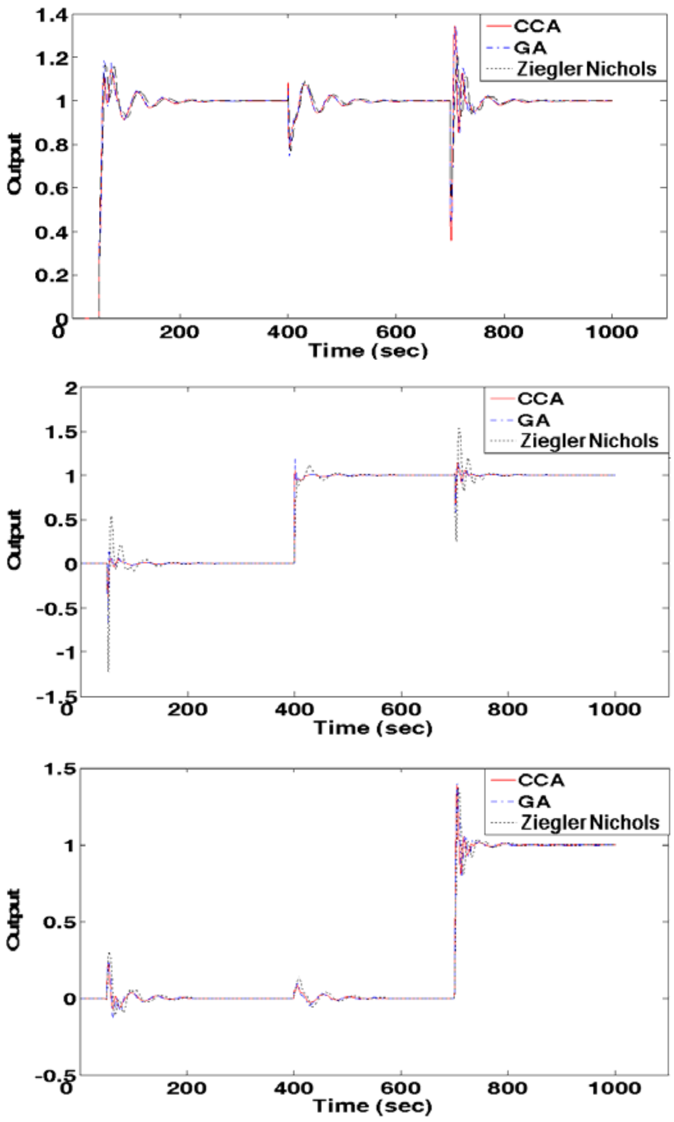

Fig. 6. The response of controlled evaporator process to step inputs using controllers obtained by decentralized method and then tuned by CCA, GA (Up: Output 1, Middle: Output 2, Down: Output 3).

The step responses in Fig. 6, paraphrase the results of Table 3. For the first output, CCA tracks the first input better than others but GA and Zeigler-Nichols methods are less affected by other channels, in comparison with CCA. Considering the second output step responses, CCA and GA have approximately the same performances. However, as the Table 3 indicates, CCA is a little better than GA. Finally, CCA has significantly resulted in the best performance in tracking the third input and rejecting the effects of other ones. To have a better sense of values given in Tabel 3, these values are drawn as a bar chart in Fig. 7.

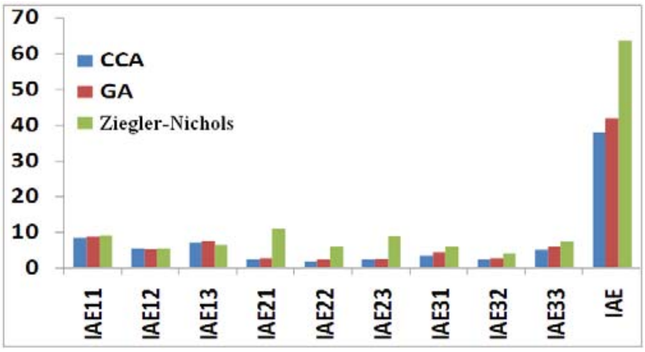

Fig. 7. The bar chart of the values in Tabel 3.

5. CONCLUSION

In this paper the multivariable model of evaporator plant was identified using prediction error model. A decentralized PID controller was designed for the identified plant using Ziegler-Nichols designing method. The performance of controlled process was improved through tuning PID coefficients using two evolutionary algorithms, GA and CCA. The design objective in these evolutionary algorithms was to tune the PID controller to minimize the integral of absolute errors. The results showed that CCA had a higher convergence rate than that of GA and also controlled outputs in CCA had generally better characteristics than those of GA and Ziegler_Nichols method. The results of controllers obtained by CCA and GA had better performance in minimizing the integral of absolute errors.

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