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An Intelligent Control System Design for an Evaporator based on Particle Swarm Optimization

Hala A. Abdel-Halim
Hot Laboratory and Waste Management Center, AEA, Cairo, Egypt. P.O 13759

Othman E. A.
Computers and Systems Eng. Dept., Zagazig Univ., Zagazig, Egypt.

A. A. Sakr
Hot Laboratory and Waste Management Center, AEA, Cairo, Egypt. P.O 13759

A. A. Zaki
Hot Laboratory and Waste Management Center, AEA, Cairo, Egypt. P.O 13759

A. A. Abouelsoud
Electronics and Communications Eng. Dept., Cairo Univ., Cairo, Egypt.

ABSTRACT
The main contribution of this paper is aimed to design and implementation of an intelligent level controller and intelligent 2×2 decentralized PI controller and a lead compensator for the forced circulation evaporator by using PSO strategy. The most important thing to guarantee the safe operation of the forced circulation evaporator, without damaging the installed equipment, is obtaining optimal controllers for the evaporator operating pressure and the level of liquid inside the separator part. Also the percent of the concentration of the non-volatile in the solution must be effectively controlled to required limits. PSO algorithm is implemented in MATLAB and is compared to GA strategy for design and implementation of optimal controllers for the evaporator system by minimizing the summation of the characteristics of unit step response. Also computer simulation results are compared to the different two cost functions methods by analyzing the performance, stability and robustness with respect to variation of the evaporator control system.

General Terms
Process Control, Intelligent Control, Optimal Control, Particle Swarm Optimization, Genetic Algorithm.

Keywords
Particle Swarm Optimization; Genetic Algorithm; Forced Circulation Evaporator; Performance Indices.

1. INTRODUCTION
PID controller is most widely used controller in chemical process industries because of its simplicity, robustness and successful practical application. Recently, tuning of PI/PID controller by using intelligent optimization techniques such as PSO and GA has attracted a lot of research interests [1], [2], [3], [4] and [5]. These include intelligent optimization techniques such as particle swarm optimization [6] and [7] and Genetic Algorithm [8], [9] and [10].

Controlling of chemical processes (which are basically Multi Input Multi Output systems) is not straight forward due to the coupling and interactions between channels. To overcome this challenge, tuning of decentralized PI/PID controller by using intelligent optimization techniques such as PSO and GA [11], [12], [13], [14], [15], [16], [17], [18], [19] and [20] are used due to their less complexity, high performance and easy implementation. Genetic algorithms (GAs) belong to the larger class of evolutionary algorithms, which generate solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover [21]. The genetic algorithm repeatedly modifies a population of individual solutions. At each step, the genetic algorithm selects individuals from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population "evolves" toward an optimal solution.

PSO is a robust stochastic optimization technique based on the movement and intelligence of swarms. It was developed in 1995 by James Kennedy (social-psychologist) and Russel Eberhart (electrical engineer) [22]. It is one of the strongest methods for solving optimization problems. The method is proved to be robust in solving problems featuring nonlinearity and non-differentiability, multiple optima, and high dimensionality. The advantages of the PSO are its relative simplicity and stable convergence characteristic with good computational efficiency [23]. Also PSO has advantages over GA; PSO has faster execution time than GA because it has only one operator; velocity calculation. However GA requires performing selection, crossover and mutation operations, so implementation of PSO is easier than implementation of GA [24].

In the previous work [25], we employed genetic algorithm GA to obtain the optimum parameters of an evaporator control system by using different tuning methods. The proposed method using cost functions Integral of Square Error ISE plus summation of step response parameters such; rise time Tr, settling time Ts, maximum overshoot Mp and steady state error Ess. (ISE + SRP) and (IAE+SRP) were more efficient, stable and robust compared with the ordinary tuning methods using performance indices only, such as Integral of Absolute Error (IAE), Integral of Square Error (ISE), Integral of Time Absolute Error (ITAE) and Integral of Time multiplied with Square Error (ITSE).

This paper utilizes PSO algorithm and comparing to GA strategy for design and implementation of optimal controllers for the evaporator system by minimizing the summation of the characteristics of step response. Also simulation results are compared to the different two cost functions methods.

This paper contains 7 sections beside the introduction. In section 2 the proposed objective function and the other used two objective functions groups are presented. Section 3 explains particle swarm optimization technique in details. Section 4 devoted for describing in details the used evaporation system. Applying GA and PSO to obtain the parameters of level control and to choose the parameters of the decoupler controller for evaporator system are illustrated in section 5. Section 7 gives the conclusion of paper.

2. OBJECTIVE FUNCTIONS

Performance index is a measure of a system's performance that confirms the characteristics of the system's response which are considered important [26].
The well-known integral performance indices as follow:

- Integral Absolute Error (IAE)= $\int_0^t |e(t)| dt$
- Integral Square Error(ISE)= $\int_0^t e^2 dt$
- Integral Time Absolute Error (ITAE) =$\int_0^t t|e(t)| dt$
- Integral Time Square Error (ITSE) =$\int_0^t te^2 dt$.

Where t is the time interval and e (t) is the difference between set point and controlled variable.

Most researches take some or all of the previous integral performance indices as cost functions in optimal control design and analysis the control system performance by investigating the parameters of time response parameters. So in this paper, we propose a simple and a direct cost function that is the summation of step response parameters only as follows;

- $SPR = \omega_0 . T_r + \omega_1 . T_S + \omega_2 . M_P + \omega_2 . E_{ss}$

Where T_r is Rise Time, T_S is settling Time, M_P is Maximum Overshoot and E_{ss} is steady state error

And constants ω_0, ω_1 *and* ω_2 should be selected by the designer according to the case. In our case, take these parameters equal to 1.

This cost function is compared with two groups of cost functions;

- First group considers integral performance indices separately;

* IAE, *ISE, * ITAE, *ITSE

- Second group considers integral performance indices separately plus Step response parameters;

* IAE+SRP, * ISE+SRP, * ITAE+SRP, *ITSE+SRP

3. PARTICLE SWARM OPTIMIZATION

PSO as a population-based evolutionary algorithm is an optimization method based on natural behaviour of birds flocking or fish [22]. All solutions in PSO can be represented as particles in a swarm. Each particle has a position and velocity vector and each position coordinate represents a parameter value. Similar to the most optimization techniques, PSO requires a fitness evaluation function relevant to the particle's position. X_{PB} and X_{GB} are the personal best (Pbest) position and global best (Gbest) position of the ith particle.

Each particle is initialized with a random position and velocity. The velocity of each particle is accelerated toward the global best and its own personal best based on equation (1) [27]:

$$V_i(new) = \omega \times V_i(old) + C_1 \times R1 \times (X_{PB} - X_i) + C_2 \times R2 \times (X_{GB} - X_i) \quad (1)$$

Here R1 and R2 are two random numbers in the range [0, 1]; C_1 and C_2 are the acceleration constants and ω is the inertia weight factor. The parameter ω helps the particles converge to Gbest, rather than oscillating around it.

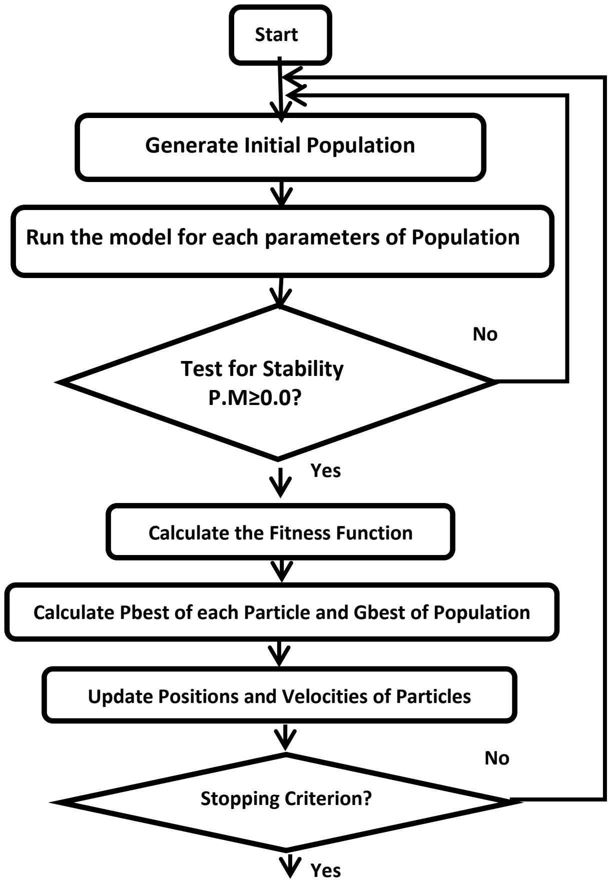

Fig. 1 Flowchart of PSO Controller Design Procedure

In this paper, acceleration constants and inertia weight factor are taken as recommended in Clerc'sPSO [28] where:

C_1=C_2=0.5 + log (2)and ω =1/ (2*log (2))

The positions are updated based on their movement over a discrete time interval (Δt) as follows:

$$X_i(new) = X_i(old) + V_i(new). \Delta t$$

Where Δt usually is set to 1. Then the fitness at each position is reevaluated. If any fitness is greater than Gbest, then the new position becomes Gbest, and the particles are accelerated toward the new point. If the particle's fitness value is greater than Pbest, then Pbest is replaced by the current position. The flowchart of PSO algorithm is illustrated in Fig.1.

The PSO algorithm parameters used are:

- 10 particles in each population
- 100 generations

In this Paper, PSO technique is implemented by using MATLAB [28].

4. EVAPORATION SYSTEM

The Particle swarm optimization and genetic algorithms are applied to the evaporation system [29]. As shown in Fig. 2, the evaporation system is a forced circulation evaporator that is used to separate mixtures unable to be evaporated by a conventional evaporating unit. This system uses two heat exchangers (evaporator and Condenser) and separation unit (Separator) in conjunction with circulation of the solvent in order to increase the concentration of the feed solution to the required limits.

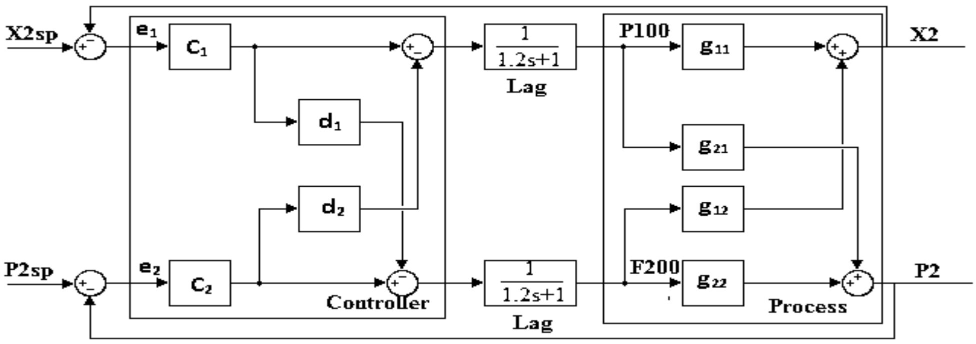

Fig. 3 Multivariable (TITO) process with decoupling controller (controllers [C_1 and C_2] and decouplers [d_1 and d_2])

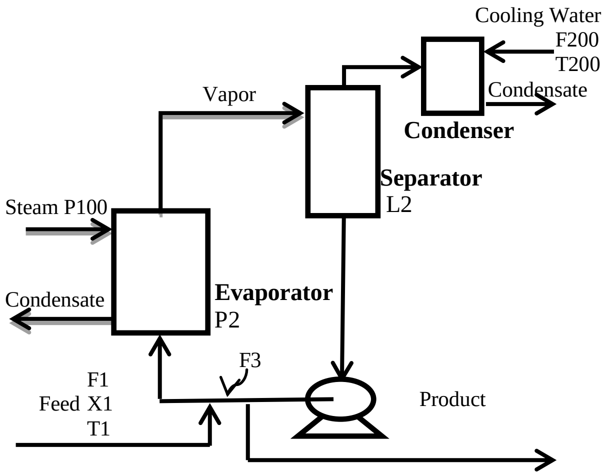

Fig 2: An Evaporator Layout

A mathematical model of the evaporator system was represented as shown in appendix A. A nonlinear mathematical model of the forced circulation evaporator was implemented using SIMULINK/MATLAB [28] as shown in Fig. (1A) in the appendix A.

The corresponding linear state space representation is as follows:

$$\begin{bmatrix} \dot{L2} \\ \dot{X2} \\ \dot{P2} \end{bmatrix} = A \begin{bmatrix} L2 \\ X2 \\ P2 \end{bmatrix} + B_i \begin{bmatrix} F2 \\ P100 \\ F200 \end{bmatrix} + B_d \begin{bmatrix} F3 \\ F1 \\ X1 \\ T1 \\ T200 \end{bmatrix} \quad (3)$$

Where: $A = \begin{bmatrix} 0 & 0.0042 & 0.0075 \\ 0 & -0.100 & 0 \\ 0 & -0.0209 & -0.0558 \end{bmatrix}$

$$B_i = \begin{bmatrix} -0.0500 & -0.0019 & 0 \\ -0.0125 & 0 & 0 \\ 0 & 0.0096 & -0.0018 \end{bmatrix}$$

$$B_d = \begin{bmatrix} -0.0089 & 0.0444 & 0 & -0.0009 & 0 \\ 0 & 0.0025 & 0.5000 & 0 & 0 \\ 0.0447 & 0.028 & 0 & 0.0045 & 0.036 \end{bmatrix}$$

A linear model is obtained from linearization the Simulink model at the nominal operating point as shown in Table 1A and Table 2A in the appendix A.

The main controlled variable is the "Product Composition" (X2). Also operating pressure (P2) and level of liquid in the separator (L2) are controlled variables for the safe operation and a voiding damaging to the installed equipment. The manipulated variables are; product flow rate (F2), steam pressure (P100) and cooling water flow rate (F200). Other variables that affect the evaporator's performance, act as disturbances, namely F3 (circulating flow rate), F1 (feed flow rate), X1 (feed composition), T1 (feed temperature) and T200 (cooling water flow rate).

5. IMPLEMENTATION OF EVAPORATOR CONTROL SYSTEM

5.1 Implementation of Level Controller

Considering the proposed PI level controller manipulates the Product Flow rate F2 to adjust separator level L2. According to the proposed cost function that the summation of step response parameters and comparing the results by the two groups of cost functions that by using PSO and GA, Table 1 and Table 2 indicate the obtained optimal parameters of PI controllers (the proportion gain (Kp), integration gain (Ki)) where each of them with a prefilter which has the gain (N) and pole (N). Also Figures (2a and 2b) show the step response of the proposed level controllers depending on the proposed cost function (SRP) and the other two cost functions groups by using GA and PSO, respectively.

5.2 Implementation of the Decoupler Controller

After controlling of the separator level L2 as illustrated in the previous section, the evaporator can be considered as Two-Input-Two-Output (TITO) multivariable system as shown in Figure 3 that by applying a decoupler controller by means of decouplers d_1 and d_2 that to cancel the interaction between control loops and leave product composition X2 is controlled only by adjusting steam pressure P100 and operating pressure P2 is controlled only by adjusting cooling water flow rate F200. Tables 3 -6 indicate by using GA and PSO respectively and according to the different cost functions, the optimal parameters of PI controllers C1 and lead compensators C2 of the decoupler controllers and illustrate the comparing results of their summation of step response parameters, gain margin (GM) and phase margin (PM). Also figures (2.1 and 2.2) show the step response of the proposed level controllers using the different cost functions by using GA and PSO, respectively. Also figures (3a, 3b, 4a, and 4b) show the unit step response of the proposed controllers C_1 and C_2 relating to the proposed cost function (SRP) and the other two cost functions groups by using GA and PSO, respectively. Table 7 summarizes the best results of the two cost functions groups and the results of the suggested cost function SRP by using GA and PSO strategies.

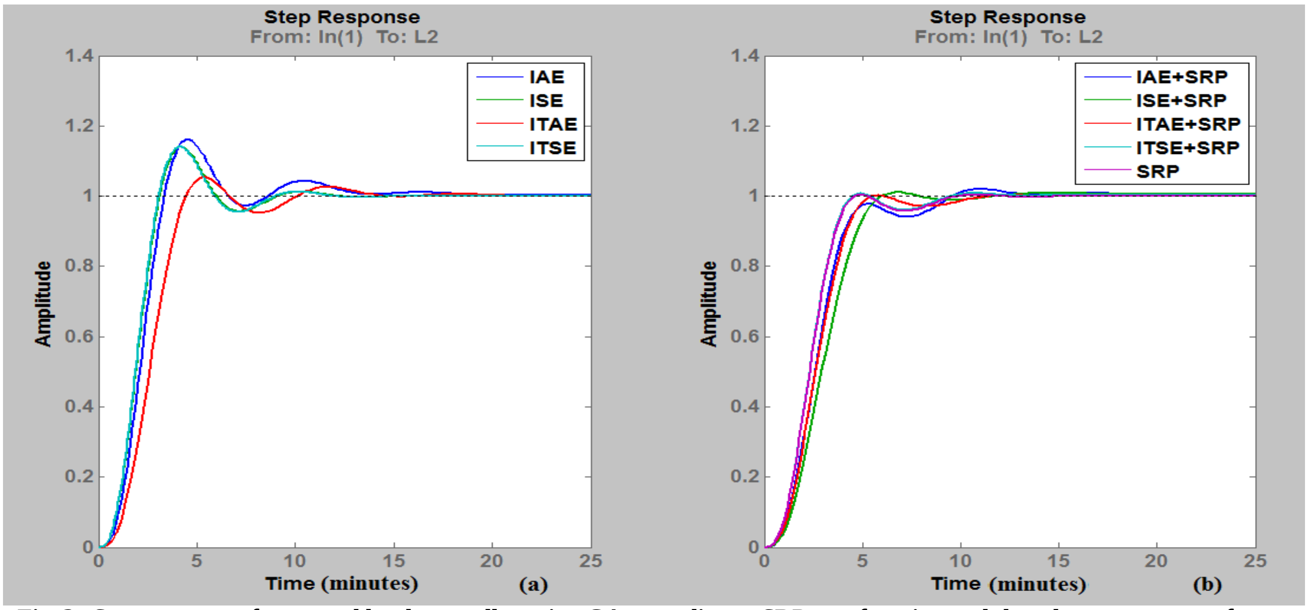

Fig. 2a Step response of proposed level controller using GA according to SRP cost function and the other two groups of cost functions

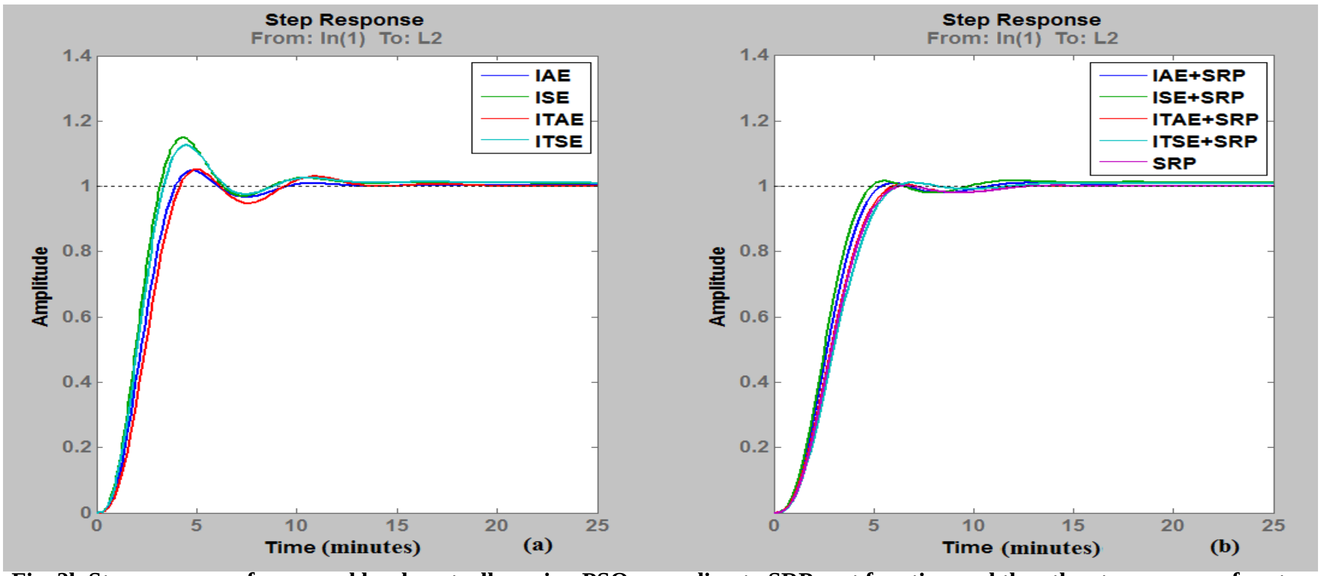

Fig. 2b Step response of proposed level controller using PSO according to SRP cost function and the other two groups of cost functions

Table 1 Parameters of proposed Level controllers using GA with two groups of cost functions and SRP cost function, also summation of step response parameters (SRP values) , their gain margin (GM) and phase margin (PM) (the dashed row indicates its best in SRP or Stability)

First group	Kp	Ki	N	SRP	GM (dB)	PM (deg)	Second group +SRP	Kp	Ki	N	SRP	GM (dB)	PM (deg)
IAE	30	4.8219	0.6365	30.33	Inf	48.19	IAE+SRP	29.6782	5.3991	0.3724	13.8	Inf	46.54
ISE	29.286	0.0001	1	24.26	Inf	64.36	ISE+SRP	18.3726	0.1333	0.5024	10	Inf	83.22
ITAE	25.995	5.9177	0.3998	20.64	Inf	45.15	ITAE+SRP	23.1784	0.0037	0.5279	12.63	Inf	73.53
ITSE	30	0.0004	1	24.24	Inf	63.5	ITSE+SRP	29.9937	0.1781	0.5626	11.75	Inf	62.91
							SRP	29.7838	0.0001	0.5643	11.55	inf	63.760

Table 2 Parameters of proposed Level controllers using PSO with two groups of cost functions and SRP cost function, also summation of step response parameters (SRP values) , their gain margin (GM) and phase margin (PM) (the dashed row indicates its best in SRP or Stability)

First group	Kp	Ki	N	SRP	GM (dB)	PM (deg)	Second group +SRP	Kp	Ki	N	SRP	GM (dB)	PM (deg)
IAE	28.3932	0.1079	0.6521	15.62	Inf	65.09	IAE+SRP	22.3411	0.2295	0.5171	8.97	inf	73.75
ISE	28.8048	0.6705	0.9224	28.20	Inf	62.54	ISE+SRP	24.9458	0.5603	0.5232	9.09	inf	67.81
ITAE	29.1052	6.384	0.4272	19.69	Inf	43.65	ITAE+SRP	19.2738	0.0019	0.5172	9.28	inf	82.03
ITSE	28.4603	0.7569	0.8196	26.30	Inf	62.60	ITSE+SRP	17.6662	0.1461	0.4945	10.25	inf	85.03
							SRP	19.0901	0.0118	0.5039	9.09	inf	82.43

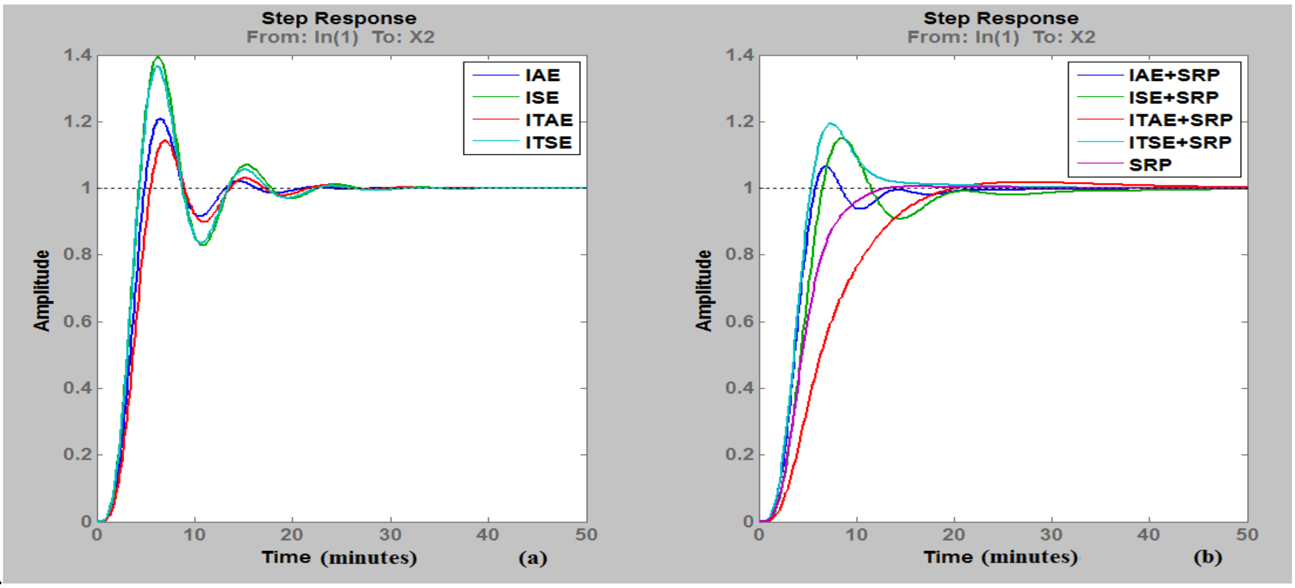

Fig. 3a Step response of proposed controllers C_1 using GA according to SRP cost function and the other two groups of cost functions

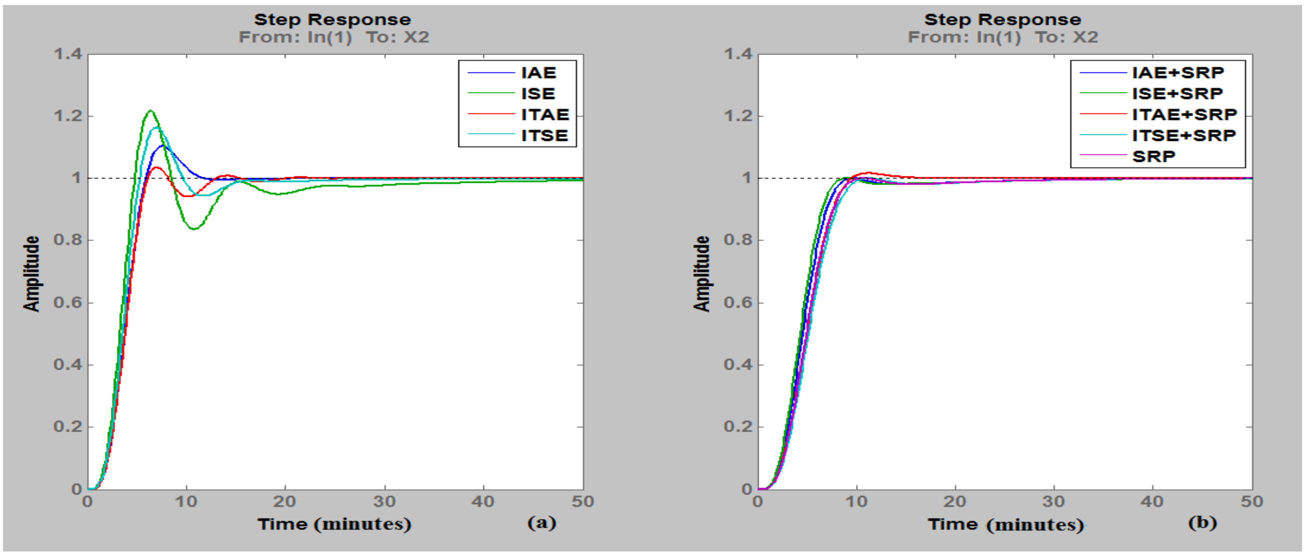

Fig. 3b Step response of proposed controllers C_1 using PSO according to SRP cost function and the other two groups of cost functions

Table 3 Parameters of proposed controllers C_1 using GA with two groups of cost functions and SRP cost function, also summation of step response parameters (SRP values) , their gain margin (GM) and phase margin (PM) (the dashed row indicates its best in SRP or Stability)

First group	Kp	Ki	SRP	GM (dB)	PM (deg)	Second group +SRP	Kp	Ki	SRP	GM (dB)	PM (deg)
IAE	689.472	70.3774	38.27	1.9443	55.23	IAE+SRP	567.387	54.5581	22.26	2.29	64.04
ISE	964.093	94.6058	62.77	1.6955	40.96	ISE+SRP	602.353	46.5112	37.52	2.27	56.41
ITAE	572.376	59.039	36.74	1.9544	61.76	ITAE+SRP	253.6	30.012	30.12	5.69	70.21
ITSE	960.395	87.6701	59.52	1.7308	42.75	ITSE+SRP	653.085	83.8868	36.1	2.45	51.6
						SRP	428.0729	44.1721	17.1574	3.83	67.59

Table 4 Parameters of proposed controllers C_1 using PSO with two groups of cost functions and SRP cost function, also summation of step response parameters (SRP values) , their gain margin (GM) and phase margin (PM) (the dashed row indicates its best in SRP or Stability)

First group	Kp	Ki	SRP	GM (dB)	PM (deg)	Second group +SRP	Kp	Ki	SRP	GM (dB)	PM (deg)
IAE	616.533	61.4936	24.0605	2.5967	58.2297	IAE+SRP	465.708	42.309	12.80	3.09	65.59
ISE	848.505	50.1403	55.8227	1.9088	52.225	ISE+SRP	489.623	44.357	11.96	3.03	65.40
ITAE	521.072	54.4077	18.9635	2.3397	65.8306	ITAE+SRP	421.334	42.3508	15.50	3.25	64.08
ITSE	703.938	61.4962	33.6499	2.2298	55.5638	ITSE+SRP	410.02	37.741	14.77	3.22	65.89
						SRP	432.247	39.525	14.09	3.19	65.80

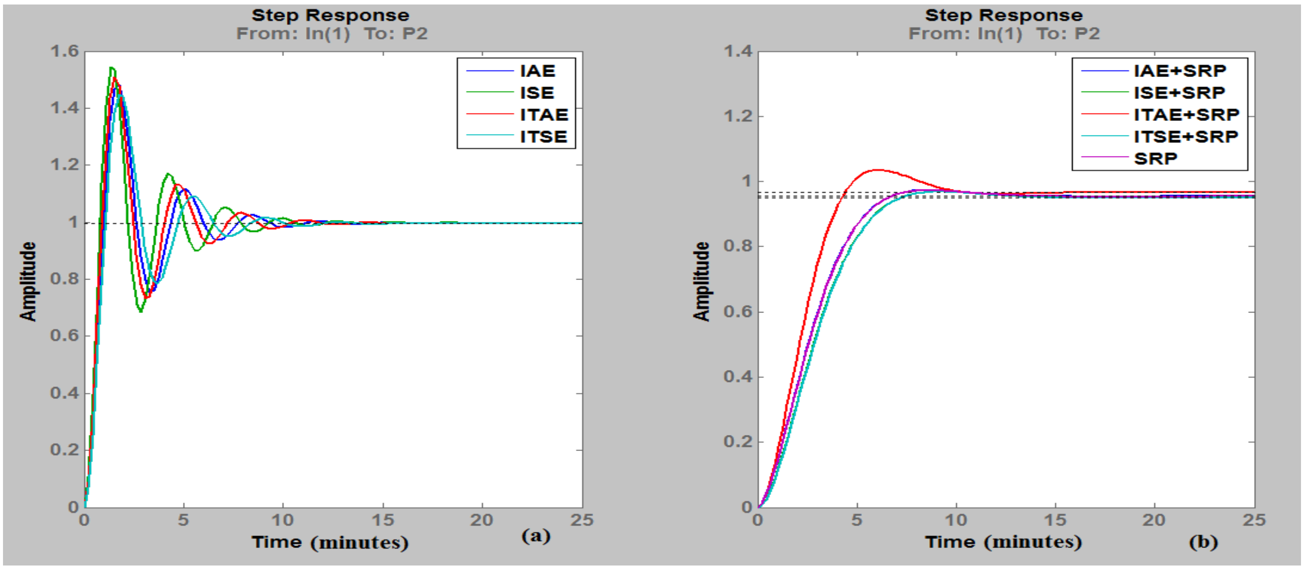

Fig. 4a Step response of proposed controllers C_2 using GA according to SRP cost function and the other two groups of cost functions

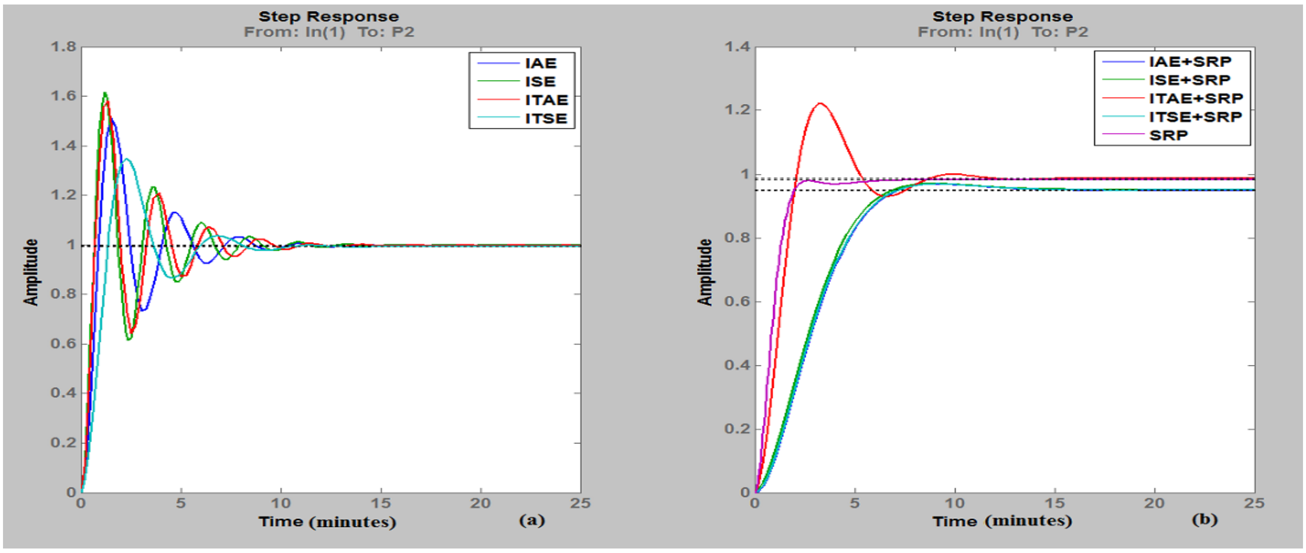

Fig. 4b Step response of proposed controllers C_2 using PSO according to SRP cost function and the other two groups of cost functions

Table 5 Parameters of proposed C_2 using GA with two groups of cost functions and SRP cost function, also summation of step response parameters (SRP values) , their gain margin (GM) and phase margin (PM) (the dashed row indicates its best in SRP or Stability)

First group	z	p	k	SRP	GM (dB)	PM (deg)	Second group +SRP	z	p	k	SRP	GM (dB)	PM (deg)
IAE	-113.6	-78.9	-1660.1	58.48	62.58	24.78	IAE+SRP	-6	-40.6	-1401.6	12.31	inf	73.08
ISE	-166.8	-77.7	-1554.6	64.27	24.86	20.55	ISE+SRP	-34	-169.3	-936.3	12.92	inf	72.57
ITAE	-200	-117.1	-1592.6	60.61	59.06	23.25	ITAE+SRP	-29.8	-153.3	-1469.3	19.02	inf	64.22
ITSE	-162.8	-151	-1909.9	55.46	612.81	27.01	ITSE+SRP	-77.4	-189.6	-457.3	13	inf	72.5
							SRP	-6.07	-41.17	-1.40E+03	12.32	inf	73.09

Table 6 Parameters of proposed C_2 using PSO with two groups of cost functions and SRP cost function, also summation of step response parameters (SRP values) , their gain margin (GM) and phase margin (PM) (the dashed row indicates its best in SRP or Stability)

First group	Z	p	k	SRP	GM (dB)	PM (deg)	Second group +SRP	z	p	k	SRP	GM (dB)	PM (deg)
IAE	-166.5	-114.3	-1870.3	60.47	76.58	23.32	IAE+SRP	-70.8	-125.1	-329.47	13.01	Inf	72.49
ISE	-149.4	-65.2	-1980.5	72.13	14.58	17.14	ISE+SRP	-11.8	-118.32	-1.97E+03	12.66	Inf	72.81
ITAE	-135.7	-65.5	-1955.1	68.15	17.91	18.39	ITAE+SRP	-42.1	-94.91	-1.59E+03	19.13	Inf	45.15
ITSE	-15.1	-22.2	-1982.2	44.47	Inf	34.67	ITSE+SRP	-38.2	-169.63	-835.78	12.4	Inf	12.94
							SRP	-0.68	-2.40	-2000	3.61	Inf	72.01

Table 7 A comparison between the results of Using GA and PSO in optimal evaporator control system

Controlled parameter	Cost functions		GA	PSO
L2	First group	Best Performance	ITAE, SRP=20.64	IAE, SPR=15.62
		Best Stability	ISE, GM=inf, PM=64.36	IAE, GM= inf, PM= 65.69

	Second group	Best Performance	ISE+SRP, SRP=9.99	IAE+SEP, SRP=8.97
		Best Stability	ISE+SRP, GM= inf, PM=83.22	ITAE+SEP, GM=inf, PM=85.03
	SRP	Best Performance	SRP=11.55	SRP =9.09
		Best Stability	GM=inf, PM=63.76	GM1=inf, PM1=82.43
X2	First group	Best Performance	ITAE, SRP=36.74	ITAE, SRP=18.96
		Best Stability	ITAE, GM=1.95, PM= 61.76	ITAE, GM=2.34, PM=65.83
	Second group	Best Performance	IAE+SRP, SRP=22.26	ISE+SRP, SRP=11.96
		Best Stability	ITAE+SRP, GM=5.69, PM=70.2	ISE+SRP GM= 3.03, PM= 65.40
	SRP	Best Performance	SRP= 17.16	SRP=14.09
		Best Stability	GM=3.83, PM=67.59	GM=3.19, PM=65.80
P2	First group	Best Performance	ITAE, SRP=52.2	ITSE, SRP=44.47
		Best Stability	ITSE, GM=612.8, PM=27.01	ITSE, GM=inf, PM=34.66
	Second group	Best Performance	IAE+SRP, SRP=12.31	ISE+SRP, SRP=12.66
		Best Stability	IAE+SRP, GM=inf, PM=73.08	ITSE+SRP,GM=inf, PM= 72.81
	SRP	Best Performance	SRP=12.32	SRP=3.61
		Best Stability	GM= inf, PM=73.09	GM= inf, PM=72.01

6. ANALYSIS OF RESULTS

From previous results it could be concluded that:-

- The proposed implemented PSO achieves a best trade-off between performance and stability over than GA algorithm for tuning a level controller and a decoupler controller for the evaporator system.

- By using PSO and GA strategies the proposed cost function (SRP) achieves best performance and stability for the evaporator control system than the first group of cost functions; such as (IAE, ISE, ITAE, and ITSE) . Also SRP cost function gives best results in performance and stability for the evaporator control system near the best results of the second groups of cost functions. Moreover this cost function by using PSO achieves best performance in control operating pressure P2 over than the other two groups of cost functions.

-Figures (5a, 5b, 6a and 6b) confirm that ideal decoupler is achieved by using the proposed PSO and GA for the decoupler controllers for the evaporator system depending on the proposed SRP cost function and the other two groups of cost functions.

-Tables (8-11) show the degree of the robustness of the proposed evaporator control systems using GA and PSO depending on the proposed SRP cost function and the other two groups of cost functions with respect to changing the disturbance feed flow rate F1 by 30% decrease).

7. CONCLUSION

In this paper a particle swarm optimization algorithm is implemented as an intelligent procedure for designing of optimal evaporator control system. Simulation results demonstrate that our proposed method using cost function of summation of step response parameters (SRP) such; rise time Tr , settling time Ts , maximum overshoot Mp and steady state error Ess. is more efficient, stability and robust compared with the ordinary tuning methods using performance indices only. Also the proposed PSO achieves superiority over GA algorithm.

8. ACKNOWLEDGMENTS

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Appendix A:

Table 1a. Steady-State of the Evaporator Plant for the Inputs

F2 [Kg/min]	P100 [Kpa]	F200 [Kg/min]	F3 [Kg/min]	F1 [Kg/min]	X1 [%of mass]	T1 [°C]	T200 [°C]
2.0	194.7	208.0	50.0	10.0	5.0	40.0	25.0

Table 2a. Steady-State of the Evaporator Plant for the Outputs.

L2[m]	X2 [%of mass]	P2[Kpa]
1.0	25.0	50.5

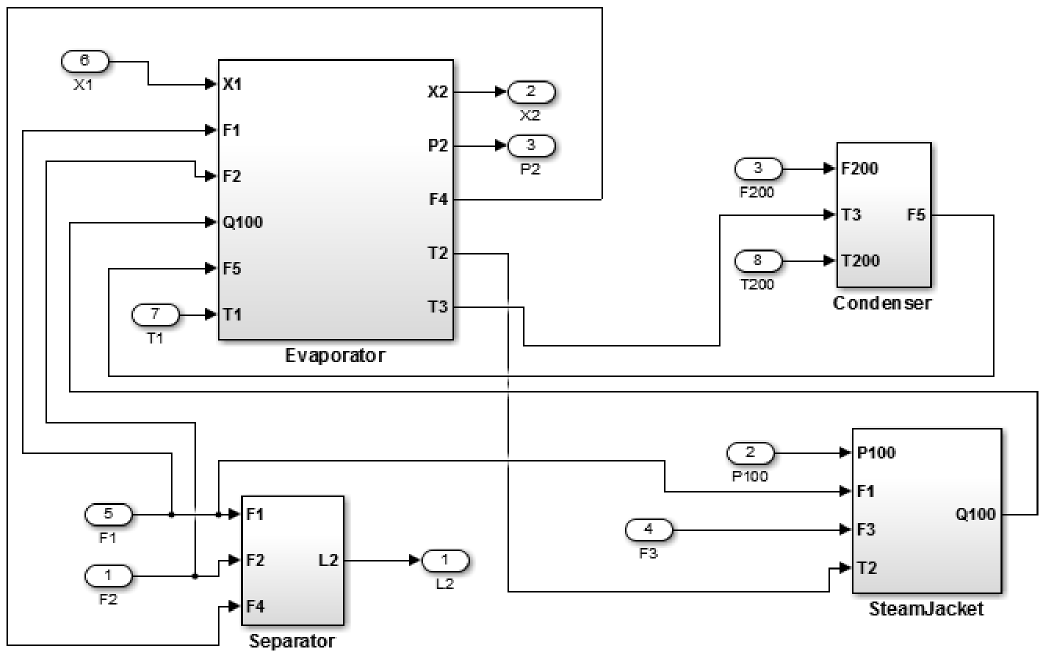

Fig 1a: A simulink model of the forced circulation evaporator consists of subsystems ([1] separator, [2]evaporator, [3]condenser, [4]steam jacket)

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10. APPENDIX

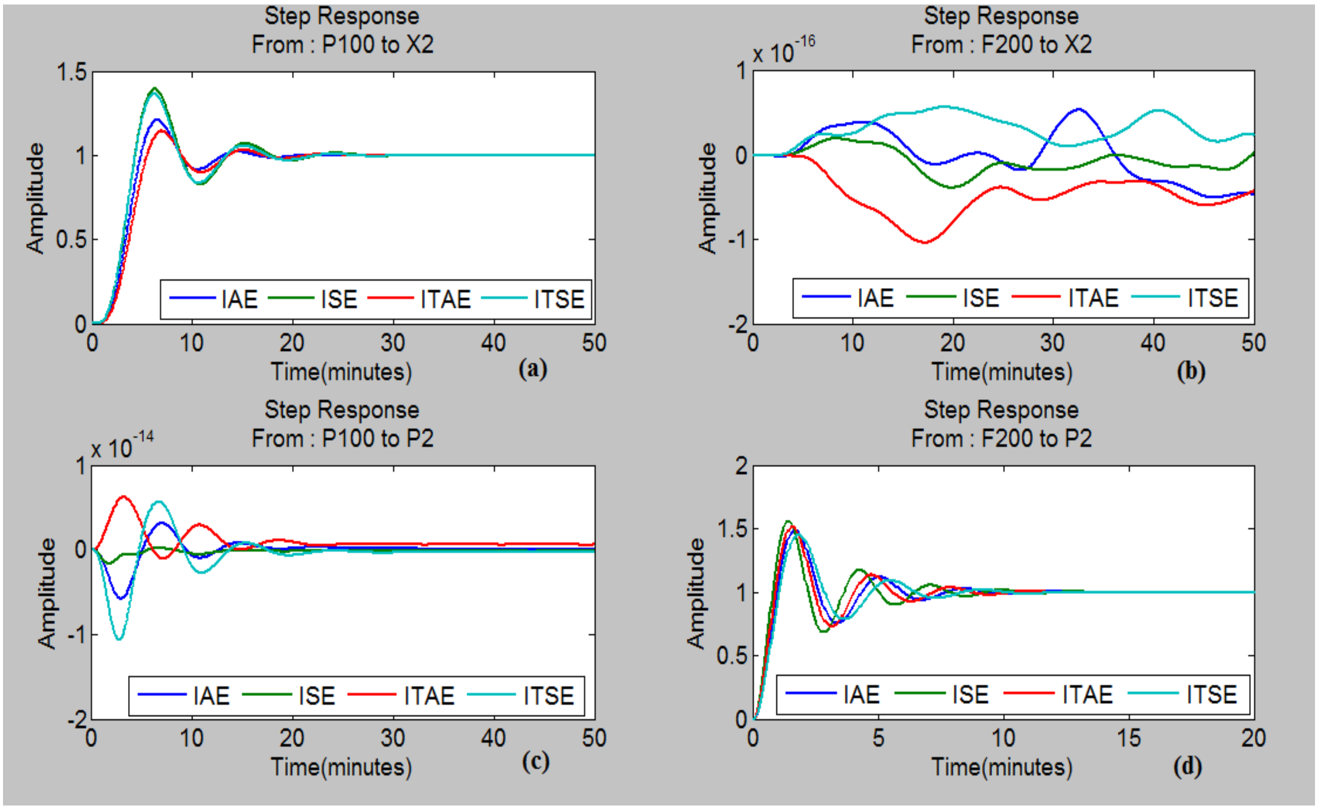

Fig. 5a Unit-Step response of proposed decoupler controllers using GA using first group

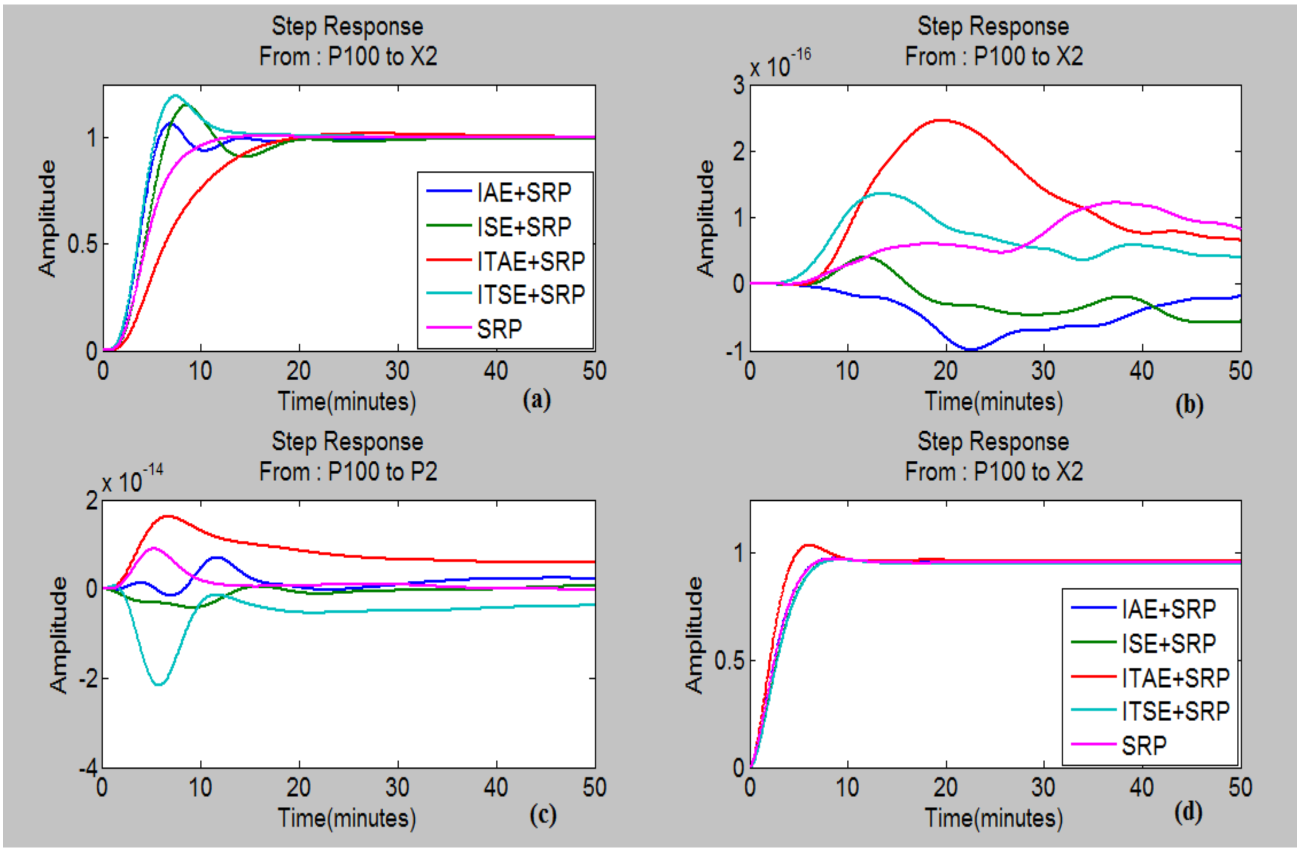

Fig. 5b Unit-Step response of proposed decoupler controllers using GA using second group and SRP cost function

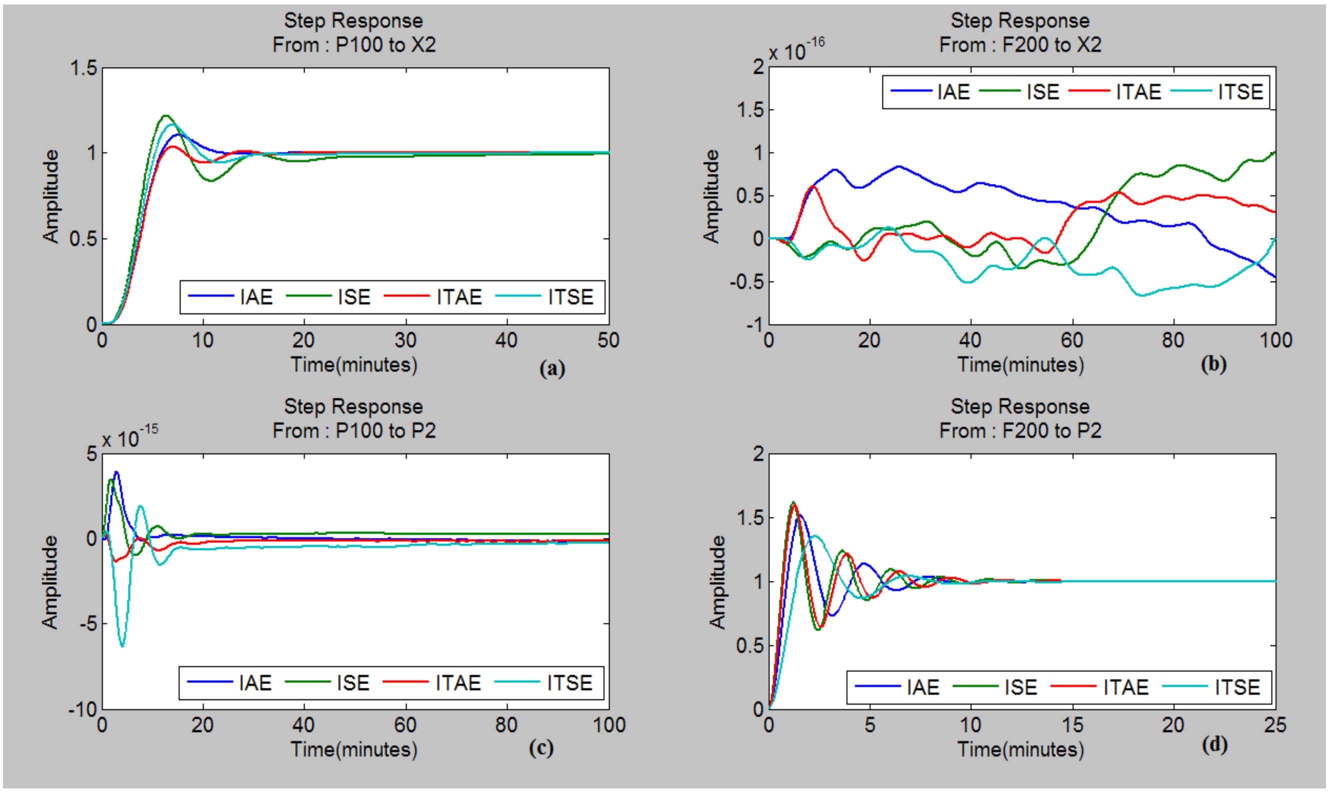

Fig. 6a Unit-Step response of proposed decoupler controllers using PSO using first group

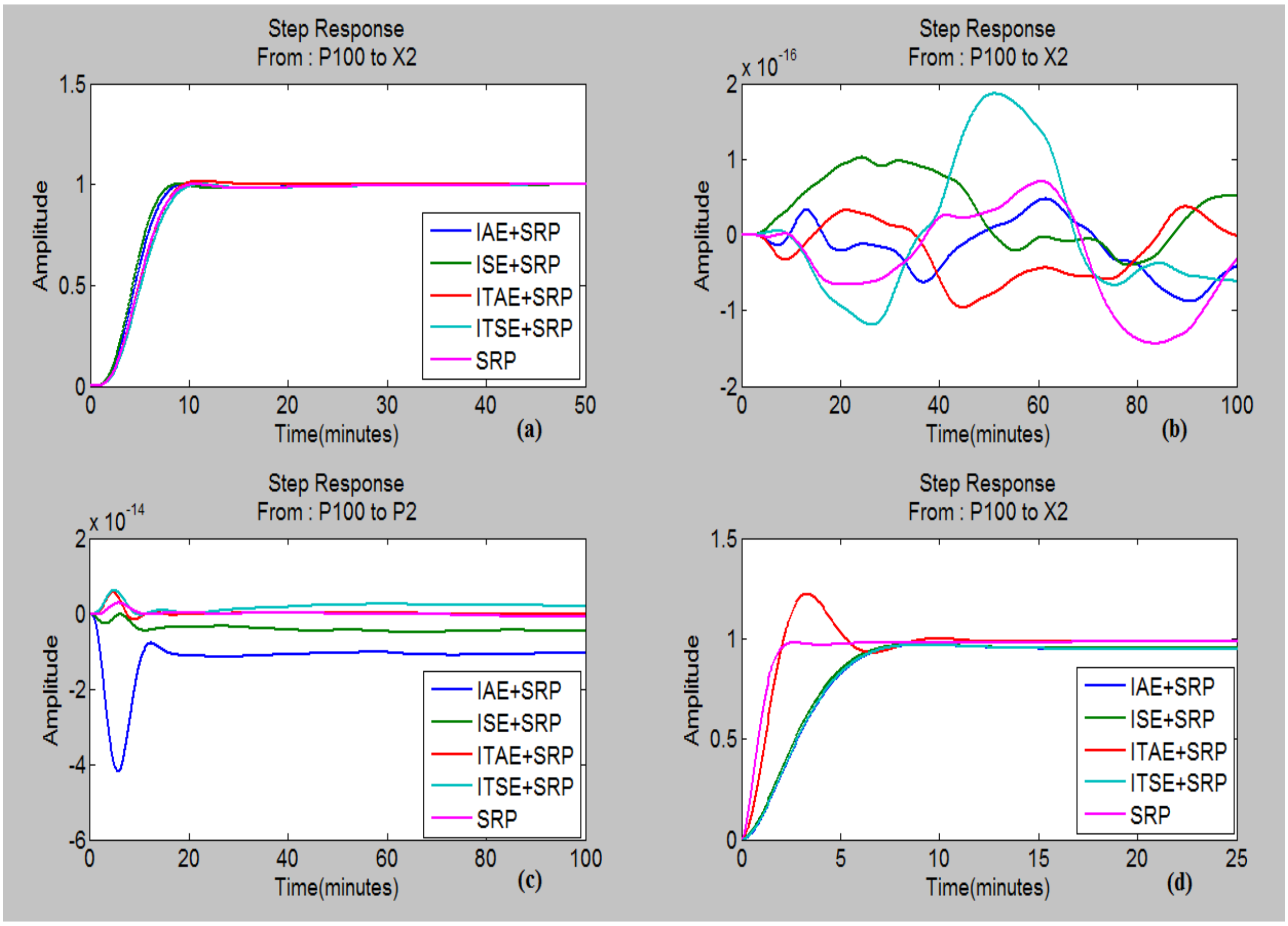

Fig. 6bUnit-Step response of proposed decoupler controllers using PSO using second group and SRP cost function

Table 8 Parameters of proposed controllers C_1 using GA with two groups of cost functions and SRP cost function, also summation of step response parameters (SRP values) , their gain margin (GM) and phase margin (PM) to step change in disturbance variable F1 of 30% decrease (the dashed row indicates its best in SRP or Stability)

First group	SRP	GM (dB)	PM (deg)	Second group +SRP	SRP	GM (dB)	PM (deg)
IAE	32.8003	2.045	56.929	IAE+SRP	19.351	2.4108	65.3154
ISE	55.6497	1.7823	43.2506	ISE+SRP	35.5014	2.3859	58.2211
ITAE	30.0952	2.0554	63.2282	ITAE+SRP	45.5589	5.981	70.0976
ITSE	52.1825	1.8195	45.0237	ITSE+SRP	35.979	2.5735	52.6668
				SRP	18.5872	4.0292	68.0896

Table 9 Parameters of proposed controllers C_1 using PSO with two groups of cost functions and SRP cost function, also summation of step response parameters (SRP values) , their gain margin (GM) and phase margin (PM) to step change in disturbance variable F1 of 30% decrease (the dashed row indicates its best in SRP or Stability)

First group	SRP	GM (dB)	PM (deg)	Second group +SRP	SRP	GM (dB)	PM (deg)
IAE	22.4082	2.7293	59.4183	IAE+SRP	14.2114	3.251	66.5095
ISE	52.3506	2.0067	54.5188	ISE+SRP	13.3474	3.1805	66.3629
ITAE	16.1838	2.4611	66.8516	ITAE+SRP	16.5046	3.4151	64.8159
ITSE	30.8226	2.3439	57.1797	ITSE+SRP	16.224	3.387	66.7223
				SRP	15.5362	3.352	66.667

Table 10 Parameters of proposed controllers C_2 using GA with two groups of cost functions and SRP cost function, also summation of step response parameters (SRP values) , their gain margin (GM) and phase margin (PM) to step change in disturbance variable F1 of 30% decrease (the dashed row indicates its best in SRP or Stability)

First group	SRP	GM (dB)	PM (deg)	Second group +SRP	SRP	GM (dB)	PM (deg)
IAE	58.4991	62.5228	24.7556	IAE+SRP	15.3988	Inf	72.9687
ISE	65.2869	24.8395	20.5312	ISE+SRP	16.0629	Inf	72.5347
ITAE	60.7945	59.0179	23.2332	ITAE+SRP	19.1347	Inf	64.1396
ITSE	55.5382	612.3213	26.9884	ITSE+SRP	16.2859	Inf	72.3856
				SRP	15.411	Inf	72.9928

Table 11 Parameters of proposed controllers C_2 using PSO with two groups of cost functions and SRP cost function, also summation of step response parameters (SRP values) , their gain margin (GM) and phase margin (PM) to step change in disturbance variable F1 of 30% decrease (the dashed row indicates its best in SRP or Stability)

First group	SRP	GM (dB)	PM (deg)	Second group +SRP	SRP	GM (dB)	PM (deg)
IAE	60.511	76.5183	23.3035	IAE+SRP	16.2947	inf	72.3737
ISE	72.1792	14.5662	17.1302	ISE+SRP	15.8744	inf	72.6771
ITAE	68.1375	17.8967	18.3631	ITAE+SRP	19.1743	inf	45.0975
ITSE	44.5632	inf	34.634	ITSE+SRP	16.2059	inf	72.4374
				SRP	3.6248	inf	71.9752