TUNING OF A PID CONTROLLER IN A SWITCHING REGULATOR USING PARTICLE SWARM OPTIMIZATION

Mohamed Azab
Faculty of Engineering, Benha University, Egypt
Pe_bhit@yahoo.com, azabm@rcyci.edu.sa

Abstract: *In this paper, the particle swarm optimization method has been employed to determine the optimum gains of a PID controller used in load voltage control of a dc buck converter. The PSO-based PID tuning technique is investigated with several design criteria such as minimization of overshoot, and integral time absolute error (ITAE). The dc chopper control system is investigated with different tuning approaches such as: Conventional empirical methods (Ziegler-Nichols & Cohen-Coon). Simulation studies proved that the PID controller tuned by PSO reveals superior response and good load regulation compared to the well-known ZN & CC methods. Moreover, the results have shown that PSO based tuning methods are stable and robust to wide load variation.*

Key words: *PARTICLE SWARM OPTIMIZATION, PID CONTROLLER, AUTO TUNING, BUCK CHOPPER.*

1. Introduction

Although many sophisticated control techniques have been proposed during the last two decades, the majority of industrial processes are still regulated by PID controllers due to their simple structure, and satisfactory performance. More than 90 % of control systems are still PID controllers [1]. However, properly setting of the PID gains to satisfy the control goal(s) is a relatively difficult task in many industrial plants that are often subjected to problems such as: high orders; time delays; and nonlinearities. Thus, tuning the controller parameters to achieve the required control performance is mandatory [2]. Many tuning formulae have been proposed. However, the most used technique is still the well known Ziegler-Nichols tuning formula which mainly provides a large overshoot and a big settling time in step response so that it is often refined by the human operator experience. Recently evolutionary computation techniques have been proposed to tune the PID controller [3,4,5,6,18]. Despite the simple concepts involved, GA takes long time to reach the solution.

Particle Swarm Optimization (PSO) is a relatively new computational intelligence technique developed by Eberhart and Kennedy in 1995, inspired by social behavior of bird flocking or fish schooling. Compared to GAs, PSO algorithms do not need any gradient information or calculation of gradient [7]. Therefore, PSO has a salient ability for optimization of non-linearly function and multi-dimensional function. In addition, PSO can be easily implemented, since its memory and CPU speed requirements are low.

The objective of this paper is to utilize the PSO technique to find the optimal values of PID controller for a load voltage control of a dc step down chopper that is subjected to different loading conditions. Compared to empirical tuning methods, the tuned values of the PID controller with PSO method result in better dynamic and steady state performance.

The rest of the paper is organized as follows: In Section 2, the main concept of a PID controller is introduced, while problem formulation is presented in section 3. Section 4 gives an overview of PSO technique. Description of the investigated system and details of applying PSO in PID controller of dc buck chopper are presented in Section 5. Selected simulation results and comparison with other methods are presented and analyzed in Section 6.

2. Overview of a PID Controller

The PID controller shown in Fig.1 has the following standard form in the time domain:

$$u(t) = K_p\, e(t) + K_i \int_0^t e(t)\,\mathrm{dt} + K_d \frac{d}{dt} e(t) \qquad (1)$$

$$e(t) = y_r(t) - y(t) \qquad (2)$$

The transfer function of the PID controller is written below:

$$\mathrm{G_{pid}(S)} = K_p + \frac{K_i}{\mathrm{S}} + K_d\,\mathrm{S} \qquad (3)$$

Where K_p is the proportional gain, K_i is the integrator gain, K_d is the differentiator gain, *e(t)* is the error signal, which is the difference between the reference

(desired) value and the actual output, while *u(t)* is the controller output. The proportional controller K_p has the effect of reducing the rise time, and reduces (but does not eliminate) the steady-state error.
An integral control K_i has the effect of eliminating the steady-state error, but it would deteriorate the transient response. A derivative control K_d improves the stability of the system by reducing the overshoot, and improving the transient response.

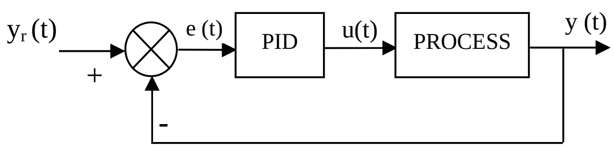

Fig. 1 Block diagram of a closed loop control system

3. Problem Formulation

PID controller is not robust to wide parameter varying and large external disturbance [1]. It is essential to tune the controller parameters to achieve good control performance. This is also essential for systems with large time delay as in [16], and for nonlinear systems as in [17]. Using the well-known Ziegler-Nichols formula generally results in good attenuation of load disturbance but also results in a large overshoot and settling time for a step response that might not be accepted for a number of processes [6]. The tuning of PID controller parameters can be viewed as an optimization problem in multi-modal space as many settings of the controller can yield good performance [6].
Several performance indices can be used in the optimum design of PID controller. The most common criteria are:

1. Integral of Absolute Error: IAE = $\int_0^{\tau} |e(t)|\, dt$

2. Integral of Time multiplied by Absolute Error:

$$\text{ITAE} = \int_0^{\tau} t\, |e(t)|\, dt$$

3. Integral of Time multiplied by Squared Error:

$$\text{ITSE} = \int_0^{\tau} t\, e(t)^2\, dt$$

Accordingly, the objective of the tuning/optimization method is to search the proper values of K_p , K_i and K_d that minimize one of the previous performance indices according to the process requirements.

4. Particle Swarm Optimization Technique

A. Concept

PSO is one of evolutionary computation techniques that is reliable in solving nonlinear problems with multiple optima. PSO is initialized with a group of random particles (solutions), and searches for optima by updating generations. Each particle in swarm represents a solution to the problem and it is defined with its position and velocity [8]. All of the particles have fitness values based on their positions and have velocities, which direct the flight of the particles. In every iteration, each particle is updated by two best values [10]. The first one is the best solution the particle has achieved so far. This value is called local best (*L*). The second best value is the best value obtained so far by any particle within the neighborhood. This is the best particle among the entire population, and is called global best (*G*). After finding the two best values, the particle updates its velocity and position with following equations:

$$v_i(k+1) = w v_i(k) + c_1 r_1 [L_i(k) - x_i(k)] + c_2 r_2 [G(k) - x_i(k)] \quad (4)$$

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (5)$$

Where: w is the inertia weight factor; $v_i(k)$ is the particle velocity at iteration k; $x_i(k)$ is the particle position in the search space at iteration k; c_1 and c_2 are positive constants called acceleration constants; r_1 and r_2 random numbers between (0,1).

B. Algorithm Description

The PSO algorithm is divided into the following major steps:

1. **Initialization:** In this step, the PSO solution (K_p , K_i , K_d) is initialized randomly.
2. **Evaluation of the initial population:** where the objective function for all particles in the initial population is evaluated.
3. **Updating position and velocity:** The velocity and position of the particles are updated according to eqns. (4) and (5).
4. **Evaluation of the updated solution:** The updated position of particles are evaluated according to their fitness; the local best *(L)* and global best (G) particles will be updated.
5. **Repeat the updating process**: If the terminal condition (number of iterations) has not been satisfied, the updating process will be repeated; otherwise, the optimization process ends.
6. **Output results:** The best solution obtained during the optimization process (G), for all PID controller parameters (K_p , K_i , K_d) is the output.

5. Description of the Investigated System

The block diagram of the investigated system is shown in Fig. 2, where a dc buck chopper supplied from a fixed dc source of 12 V is used to regulate the voltage of a dc load through a closed loop control. The control voltage U_C, which is the output of the PID controller is used to operate the buck chopper at varying duty cycle with the aid of PWM unit such that the load voltage is well controlled to the reference (desired) value.

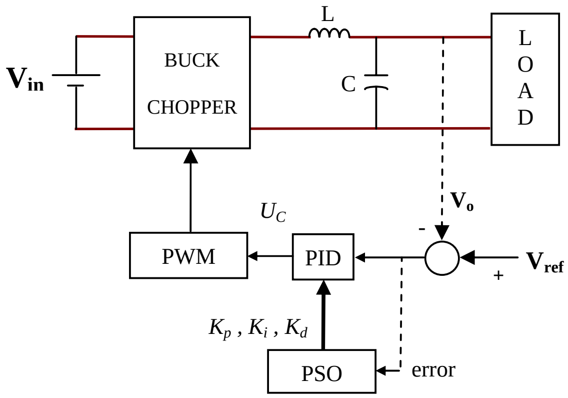

Fig. 2 Block Diagram of the Investigated System

A. Operation of the Buck Chopper

The circuit diagram of the dc buck chopper is shown in Fig. 3. By varying the duty cycle, the average value of the load voltage is controlled. The dc output voltage is regulated against load disturbance and dc input change by sensing the dc output voltage and controlling the switch duty cycle in a closed loop control. Assume that the chopper is operating in the continuous mode of operation. Thus, the average value of the output voltage is determined by eqn. 6:

$$V_{o\,AVR} = D\,V_{in} \tag{6}$$

Where $V_{o\,AVR}$ and V_{in} are the average input and output voltages of the buck chopper respectively, and the D is the chopper duty cycle.

The dc buck chopper is modeled in state-space form based on the following equations:

$$\dot{x}(t) = A\,x(t) + B\,u(t) \tag{7}$$

Assuming $x_1 = i_L$, and $x_2 = V_C$

$$\begin{bmatrix} i'_L \\ V'_C \end{bmatrix} = \begin{bmatrix} 0 & -1/L \\ 1/C & -1/RC \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} S/L \\ 0 \end{bmatrix} u(t) \tag{8}$$

Where i_L is the inductor current, V_C is the capacitor voltage, u(t) is the input voltage of the buck chopper which is defined as V_{in} as shown in Fig. 3 , and S is the switching state of the buck chopper (0 or 1). Using the hypotheses of high frequency switching of the chopper power transistor, we can approximate S by D (duty cycle)

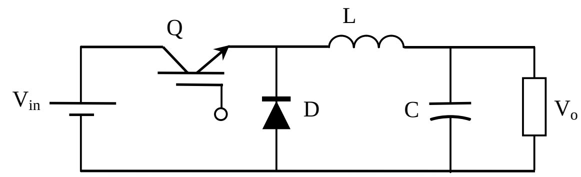

Fig. 3 Circuit Diagram of the DC Buck Chopper

The buck chopper is investigated with a circuit-based model using Sim-Power-Systems Block Set under Matlab as shown in Fig. 4. All circuit parameters of the buck chopper such as: switching frequency, R, L, C, V_{in} , Snubber circuit, DIODE On-resistance, and MOSFET On-resistance can be adjusted to emulate the actual power electronic circuit.

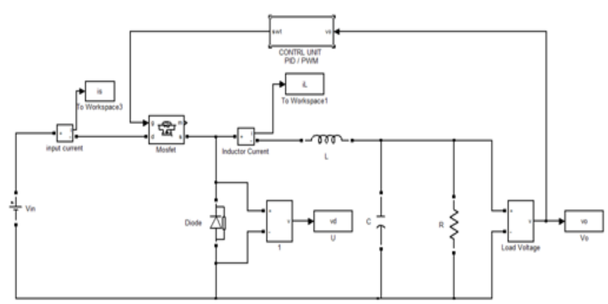

Fig. 4 Circuit-Based Model of a Buck Chopper in Sim-Power-Systems Block Set

B.Tuning of the PID Controller

The block diagram of the PSO-based PID tuning system is shown in Fig. 5. The PSO algorithm requires measurement of error signal between the reference value and the actual value of the chopper load voltage, while the output from the algorithm are the tuned values of PID controller gains: K_p K_i K_d which satisfy a certain performance index such as:

$$J_1 = \min\ (\text{IAE}) = \min\ \left(\int_0^{\tau} |e(t)|\, dt \right) \tag{9.a}$$

$$J_2 = \min\ (\text{ITAE}) = \min\ \left(\int_0^{\tau} t\,|e(t)|\, dt \right) \tag{9.b}$$

$$J_3 = \min\ (\text{ITSE}) = \min\ \left(\int_0^{\tau} t\, e(t)^2\, dt \right) \tag{9.c}$$

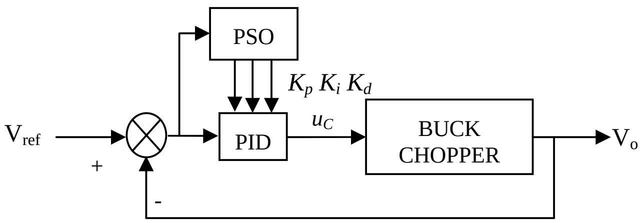

Fig. 5 Block diagram of chopper control system with self tuning PID controller

An illustrative flowchart of the PSO algorithm used to search the optimum values of PID controller gains is presented in Fig. 6.

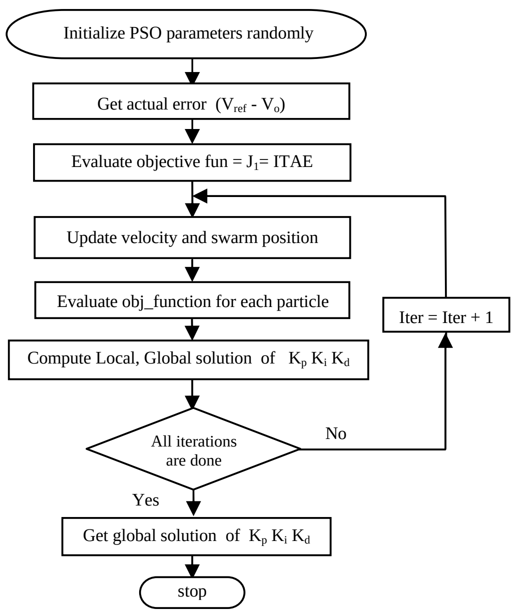

Fig. 6 Flowchart of PSO algorithm

The parameters used for PSO algorithm are illustrated in Table 1.

Table 1 Parameters used for PSO Algorithm

PSO parameter	Value
Swarm size	15
Maximum number of iterations	15
Inertia weight factor *w*	0.9
c_1 , c_2 , r_1 , r_2	Random [0,1]

The proposed tuning system is simulated and studied using Matlab/Simulink and Sim Power Systems.

6. Simulation Results

The PID controller incorporated with the chopper control unit has been tuned for the gains: k_p, k_i and k_d using the following methods:

1- PSO technique for several performance indices.
2- Ziegler-Nichols method.
3- Cohen-Coon method.

Simulation studies were conducted for the same operating conditions for step change in reference voltage from 0 to 5 V, followed by 20 % load disturbance after steady state operation. Simulation parameters related to the system under investigation are summarized in Table 2.

Table 2 Simulation Parameters

Parameter	Value
Solver	ODE 15s
L	3 mH
C	1000 μF
Load : R	1 Ω
Switching Frequency	2.5 kHz
V_{in}	12 V

The simulation results are divided into two groups:

1- The first group of results demonstrates the validity and capability of the PSO-based tuning method for different performance indices.
2- The second group of results is a comparison between Ziegler-Nichols, Cohen-Coon empirical methods with the proposed PSO-based tuning technique.

A. PSO-Based Results

Fig. 7 presents the step responses of the chopper control system whose PID controller is tuned by PSO for different design criteria. The selected design criteria are:

1- $J_1 = e(t)$

2- $J_2 = \int_0^{\tau} e(t)^2\, dt$

3- $J_3 = \int \left(t\left|e(t)\right| + u_{control}^2\right) dt$

4- $J_4 = \int t\left|e(t)\right|\, dt$

According to the obtained results, the best obtained response was with the objective function J_4 (ITAE). With J_4 both rise time and settling time are at minimum value. In addition, no peak overshoot is observed.

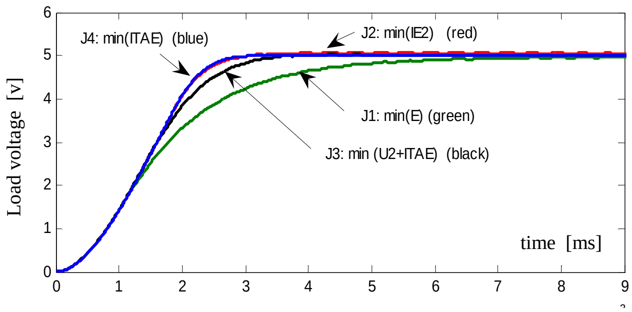

Fig. 7 Step response of PSO-based tuned PID controller With different design criteria

Moreover, load regulation has been studied for the selected design criteria. Load disturbance of 20 % is applied to chopper. The corresponding responses are plotted in Fig. 8. It has been observed that the best load regulation is obtained with J_2 (ISE) and J_4 (ITAE). The results so far prove that the PSO-based tuning method of PID controller is successful.

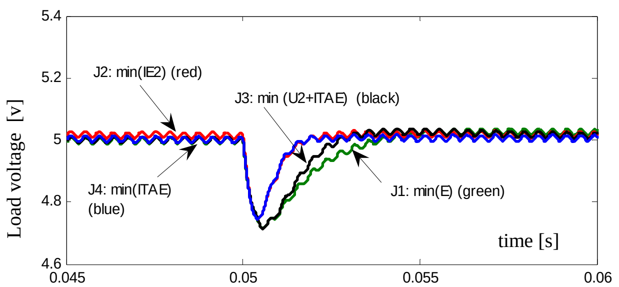

Fig. 8 Load regulation of PSO-based tuned PID controller with different design criteria (load disturbance is 20 %)

In Table ,3 the optimal values of PID controller parameters obtained using the proposed PSO tuning method are presented for different performance indices. The proposed tuning method does not require any special initial guess values in order to reach the optimal solution.

Table 3 Optimal gains of PID controller with PSO method

PSO-based Design Criteria	K_p	K_i	K_d
J_1: min(E(t))	6.7	516.7	0.008
J_2: min(ISE)	12.59	404.5	0.0068
J_3: min(ITAE+U^2)	7.73	674.7	0.0057
J_4: min(ITAE)	11.52	307.1	0.0056

B. Comparison with Empirical Methods ZN &CC

Nichols-Ziegler and Cohen-Coon are empirical methods which are utilized to determine the gains of PID controller. Both of them need some information from the open loop response. Typical curve is shown in Fig. 9. The parameters T , θ, and K are determined from the step response curve where K is ratio between the actual and the reference values at steady state (A_0/B_0).

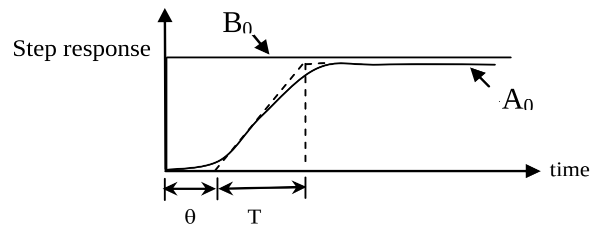

Fig. 9 Required parameters from open loop step response Curve to be used in ZN and CC tuning methods

Once these parameters are determined graphically, the tuning rules for Nichols-Ziegler and Cohen-Coon can be computed easily owing to the formulas presented in Table 4.

Table 4 Tuning rules of ZN and CC tuning methods

Tuning Method	K_p	T_i	T_d
Nichols-Ziegler	$\frac{4T}{3K\theta}$	$\frac{\theta}{0.5}$	$\frac{\theta}{2}$
Cohen-Coon	$\frac{T}{K\theta}\left(\frac{4}{3}+\frac{\theta}{4T}\right)$	$\theta\left(\frac{32+6\theta/T}{13+8\theta/T}\right)$	$\theta\left(\frac{4}{11+2\theta/T}\right)$

Fig. 10 illustrates the open loop response of the chopper load voltage. Fortunately the response satisfies a typical S-shaped curve. All the required parameters are computed, and then the PID controller parameters according to ZN and CC tuning methods are determined.

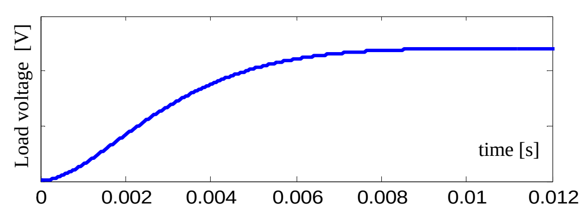

Fig. 10 Open loop response of chopper load voltage

In order to evaluate the performance of the proposed PSO-based tuning method, comparisons are carried out with ZN and CC empirical tuning methods. The results are shown in Fig. 11 and Fig. 12 for step change in the reference signal, followed by 20 % of load disturbance respectively. According to the obtained results, the performance of the overall system whose PID controller tuned by PSO is better than others whose controllers tuned by Ziegler-Nichols or Cohen-Coon methods. In both empirical methods, a great peak overshoot deteriorates the response for a step change in the reference signal or under load disturbance. While PSO-based tuning method offers good dynamic and steady state performance.

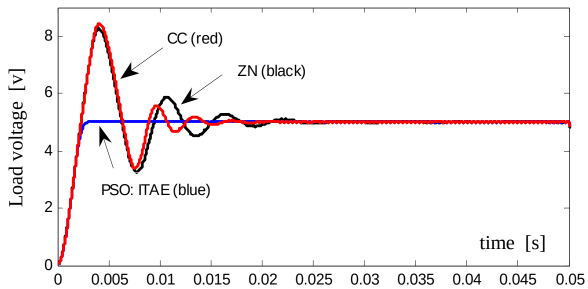

Fig. 11 Step response with PID controller tuned by different Methods: ZN , CC, PSO

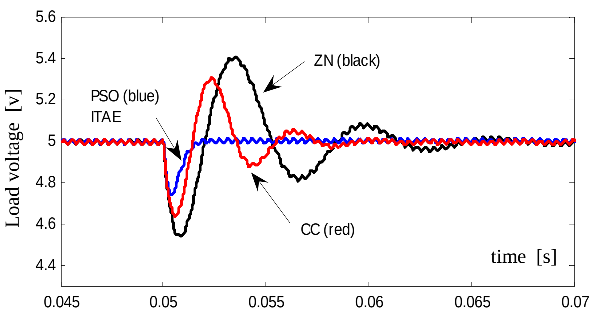

Fig. 12 Response for 20 % load disturbance with PID Controller tuned by different Methods: ZN , CC, PSO

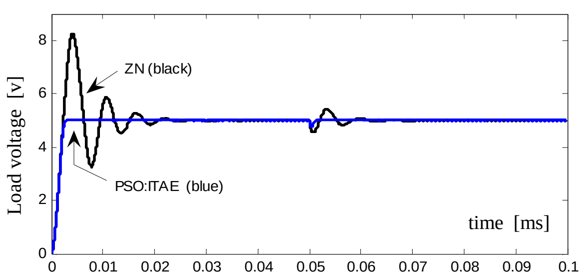

Fig. 13 Comparison between PSO-based optimal PID tuning and Ziegler-Nichols method

From the results, it is observed that Cohen-Coon tuning method is slightly better than Ziegler-Nichols. However, PSO still reveals superior response. Finally, a comparison between the well-known ZN and PSO-based method is carried out, the results are plotted in Fig. 13. The results show that the PID controller tuned by PSO guarantees non-overshoot response with a minimum settling time and offers good load regulation.

The results prove that PSO technique is able to determine efficiently the optimal values of PID controller parameters employed in voltage control of dc buck choppers.

7. Conclusion

In this paper, the PSO technique is utilized to search the optimal values of PID controller parameters in order to improve the performance of voltage control loop in a dc buck chopper. The PSO can be employed to satisfy any desired design criteria through a minimization of a certain objective function owing to the requirements of the control system. Other performance indices can be utilized to yields some goals such as minimum control effort or minimum settling time.

The chopper control system has been investigated with different tuning approaches: Ziegler Nichols & Cohen-Coon as empirical methods. According to the obtained results, the PSO-based tuning method yields a superior performance compared to empirical methods. In addition, a good load regulation, and a stable operation for changes of the input voltage have been observed with PSO-based method.

8. References

[1] Y.B. Wang, X. Peng, B.Z. Wei, "A New Particle Swarm Optimization Based Auto-Tuning of PID Controller", IEEE Int. Conf. on Machine Learning and Cybernetics, pp. 1818-1823, 2008.

[2] B. Nagaraj, S. Subha, B. Rampriya, "Tuning Algorithms for PID Controller Using Soft Computing Techniques ", Int. Journal of Computer Science and Network Security-IJCSNS, Vol. 8, No. 4, pp.278-281, 2008.

[3] D. Petr, M. Jan,"Self-tuning PID Control using Genetic Algorithm and Artificial Neural Networks", XXXIV Seminar ASR '09 "Instruments and Control", Babiuch, Smutný & Škutová (eds), pp.33-39, 2009.

[4] N. Thomas, P. Poongodi, "Position Control of DC Motor Using Genetic Algorithm Based PID Controller", Proceedings of the World Congress on Engineering, Vol II, July 1 - 3, 2009, U.K.

[5] J. s. Kim, J. H. Kim, et. al., "Auto Tuning PID Controller based on Improved Genetic Algorithm for Reverse Osmosis Plant",WASET, Vol. 47, pp. 384-398, 2008.

[6] S. Panda, N. P. Padhy, "Robust Power System Stabilizer Design using Particle Swarm Optimization Technique", International Journal of Electrical Systems Science and Engineering, www.waset.org,

pp. 1-8, Winter 2008.

[7] Mohamed Azab , "Global maximum power point tracking for partially shaded PV arrays using particle swarm optimization", International Journal of Renewable Energy Technology, vol. 1, no. 2, pp. 211-235, Inderscience Enterprises Ltd- UK , 2009.

[8] Y. Del Valle, Y. *et al.* ,"Particle swarm optimization: basic concepts, variants and applications in power systems", *IEEE Transactions on Evolutionary Computation*, April, Vol. 12, No. 2, pp. 171-195, 2008.

[9] F. Gao, and H. Q. Tong ,"A Novel Optimal PID Tuning and On-line Tuning Based on Particle Swarm Optimization", Proceedings of the International Conference on Sensing, Computing and Automation, Watam Press, pp. 182-186, 2006.

[10] J. Hereford, M. Siebold, "Multi-robot search using a physically-embedded particle swarm optimization", *International Journal of Computational Intelligence Research*, Vol. 4, No. 2, pp.197–209, 2008.

[13] Zulfatman, and M. F. Rahmat , "Application of self-tuning fuzzy pid controller on industrial hydraulic actuator using system identification approach",Int. Journal on smart sensing & intelligent systems, vol. 2, no. 2, pp. 246-261, 2009.

[14] Kyoung K. A., Bao K. N., Yoon H. S. , "Self Tuning Fuzzy PID Control for Hydraulic Load Simulator ", Int. Conference on Control, Automation, and Systems,pp. 345-349. Ceox, Seoul, Korea, 2007.

[15] X. Liu, J. Geng , S. Teng , C. Li, "A fuzzy-PID controller with adjustable factor based on S7-300 PLC , Int. Journal of Modeling, Identification and Control 2009 - Vol. 7, No.4 pp. 371 - 375.

[16] Houda Ben Jmaa Derbel," On the PID control of systems with large delays", Int. Journal of Modelling, Identification and Control 2007 - Vol. 2, No.1 pp. 66 - 71

[17] I.Mizumoto , L. Liu , H. Tanaka, Z. Iwai ,"Adaptive PID control system design for non-linear systems", Int. Journal of Modelling, Identification and Control Vol. 6, No.3 pp. 230 -238, 2009.

[18] P. Bartosz, R. Tomasz; *et.al.* , "Comparison of tuning procedures based on evolutionary algorithm for multi-region fuzzy-logi PID controller for non-linear plant", 20th International Conference on Methods and Models in Automation and Robotics MMAR, pp. 897-902, 2015.