J Electr Eng Technol.2018; 13(1): 460-467
http://doi.org/10.5370/JEET.2018.13.1.460

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Optimal PID Controller Design for DC Motor Speed Control System with Tracking and Regulating Constrained Optimization via Cuckoo Search

Deacha Puangdownreong†

Abstract – Metaheuristic optimization approach has become the new framework for control synthesis. The main purposes of the control design are command (input) tracking and load (disturbance) regulating. This article proposes an optimal proportional-integral-derivative (PID) controller design for the DC motor speed control system with tracking and regulating constrained optimization by using the cuckoo search (CS), one of the most efficient population-based metaheuristic optimization techniques. The sum-squared error between the referent input and the controlled output is set as the objective function to be minimized. The rise time, the maximum overshoot, settling time and steady-state error are set as inequality constraints for tracking purpose, while the regulating time and the maximum overshoot of load regulation are set as inequality constraints for regulating purpose. Results obtained by the CS will be compared with those obtained by the conventional design method named Ziegler-Nichols (Z-N) tuning rules. From simulation results, it was found that the Z-N provides an impractical PID controller with very high gains, whereas the CS gives an optimal PID controller for DC motor speed control system satisfying the preset tracking and regulating constraints. In addition, the simulation results are confirmed by the experimental ones from the DC motor speed control system developed by analog technology.

Keywords: PID controller, Tracking and regulating, Cuckoo search, Metaheuristics

1. Introduction

In control context, there are two main purposes of control system design [1-7]. The first one is called command tracking (or input following), while the second one is called load regulating (or disturbance rejection). In industrial applications, using the proportional-integral-derivative (PID) controllers for industrial applications was first introduced by Minorsky in 1922 [8]. To-date, the PID controller has been a worldwide solution for an effective control and more than half of industrial automatic controllers are of PID type. Not only ease of use and simple realization, but the PID also can achieve two main purposes of control as mentioned above. Tuning parameters of PID controller is a challenging work. Regarding to conventional design method for obtaining appropriate parameters of PID controller, one can proceed with available analytical design methods or tuning rules. Mostly the analytical design methods assume known plant models [1-4, 8-11] while the tuning rules assume known process responses [9, 12-13]. Those analytical design methods and tuning rules, however, have some particular conditions concerning the plant models, such as dead time or transport lag, fast and slow poles, real and complex conjugated zeros and poles, as well as unstable poles, etc. These conditions make those design methods and tuning rules non-general.

Moving toward new era, the intelligent control design has been transferred from the conventional framework to new paradigm based on modern optimization [14-15]. Finding optimal parameters of PID controller can be considered as the optimization problem. Modern optimization using the selected powerful metaheuristic techniques as an optimizer (or solver) has been accepted and applied to PID design optimization, for example of some popular metaheuristic applications, designing of the PID controller by genetic algorithm (GA) [16-23], designing of the PID controller by particle swarm optimization (PSO) [24-32] and designing of the PID controller by ant colony optimization (ACO) [33-36]. However, almost all research works considered only tracking purpose of control system design.

In 2009, the cuckoo search (CS) was firstly proposed by Yang and Deb [37] as one of the most efficient population-based metaheuristic optimization techniques. The CS algorithm is based on the obligate brood parasitic behavior of some cuckoo species in combination with the Lévy flight behaviour of some birds and fruit flies. The global convergent property of the CS algorithms has been proved and reported [38]. By literatures, the performance of the CS was evaluated against many benchmark problems including unconstraint, constraint, deterministic, stochastic, single-objective and multi-objective [37-40]. It was found

---

† Corresponding Author: Dept. of Electrical Engineering, Graduate School, Southeast Asia University, Thailand. (deachap@sau.ac.th)

Received: June 3, 2017; Accepted: August 14, 2017

that the CS is very promising and could outperform existing popular population-based metaheuristic algorithms such as GA and PSO [37-40]. Moreover, the CS has been successfully applied to several real-world engineering problems such as spring design optimization [39], welded beam design [39-40], multiple disc brake [40] and optimal PID controller design [41-43].

By literatures about applications of metaheuristic techniques to optimal PID controller design as mentioned earlier, the objective functions (error between the referent input and the controlled output) were mostly set to be minimized with tracking constraint. By those approaches, the command tracking and the steady-state responses of the controlled system would be treated, but the disturbance rejection response of the controlled system would be unpredictable. The motivation of this work is to propose the general design approach for optimal PID controller in which the command tracking and disturbance rejection responses of the controlled system will be simultaneously considered. In this article, the CS is applied to optimal PID controller design problem for DC motor speed control system based on modern optimization approach with tracking and regulating constraints. The sum-squared error between the referent input and the controlled output will be set as the objective function to be minimized. The rise time, the maximum overshoot, the settling time and the steady-state error will be performed as constraints for tracking purpose, while the regulating time and the maximum overshoot of load regulation will be set as constraints for regulating purpose. Results obtained by the CS will be compared with those obtained by one of the conventional design methods named Ziegler-Nichols (Z-N) tuning rules [12]. This article consists of five sections as follows: introduction, problem formulation of the PID controller design, CS algorithms, results and discussions and finally conclusions as appeared in section 1-4 and 5, respectively.

2. PID Design Problem Formulation

This section begins with the DC motor plant model used in this work. Then, the PID control loop and PID optimization problem with tracking and regulating constraints will be followed.

2.1 DC motor plant model

A DC motor is a useful machine transforming electrical energy to mechanical energy. It is a well-known device and widely used in industrial applications as an actuator. The schematic diagram of an armature-controlled DC motor can be represented in Fig. 1[44-45], where $e_a(t)$ is armature voltage, $e_f(t)$ is field voltage, R_a is armature resistance, L_a is armature inductance, R_f is field resistance, L_f is field inductance, $i_a(t)$ is armature current, $i_f(t)$ is field current, $e_b(t)$ is back-emf voltage, $T(t)$ is motor torque, J is moment of inertia, B is viscous friction, $\omega(t)$ is motor speed and $\theta(t)$ is motor position.

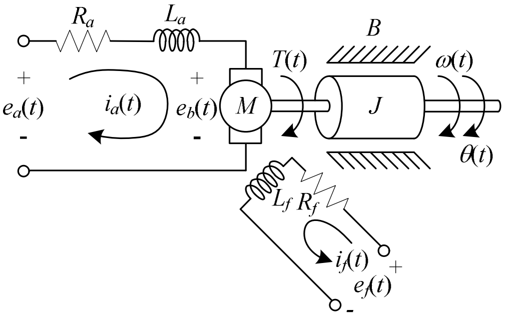

Fig. 1. Schematic diagram of DC motor

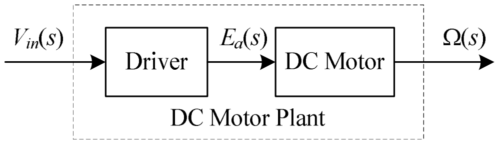

Fig. 2. DC motor plant

Once $i_f(t)$ is assumed to be constant, the induced torque $T(t)$, the armature voltage $e_a(t)$ and the back-emf voltage $e_b(t)$ can be expressed in (1), (2) and (3), respectively [4, 44-45], where K_t is torque constant and K_b is back-emf constant. By taking the Laplace transform of (1), (2) and (3), the s-domain transfer function of a DC motor can be formulated and written as stated in (4).

$$T(t) = K_t i_a(t) = J\frac{d\omega(t)}{dt} + B\omega(t) \tag{1}$$

$$e_a(t) = R_a i_a(t) + L_a\frac{di_a(t)}{dt} + e_b(t) \tag{2}$$

$$e_b(t) = K_b\omega(t) \tag{3}$$

$$\frac{\Omega(s)}{E_a(s)} = \frac{K_t}{JL_a s^2 + (BL_a + JR_a)s + (BR_a + K_t K_b)} \tag{4}$$

Commonly, using a DC motor needs a power amplifier as a driver. Due to this scheme, the DC motor plant consists of a driver and a DC motor as shown in Fig. 2. The driver model is approximated by the first-order transfer function as stated in (5), where K_A is driver gain and τ_A is driver time constant. Therefore, the DC motor plant model can be rewritten as stated (6).

$$\frac{E_a(s)}{V_{in}(s)} = \frac{K_A}{(\tau_A s + 1)} \tag{5}$$

$$\frac{\Omega(s)}{V_{in}(s)} = \frac{K_A K_t}{(\tau_A s + 1)[JL_a s^2 + (BL_a + JR_a)s + (BR_a + K_t K_b)]} \tag{6}$$

As a testing rig, the DC motor plant consists of a DC motor (LEYBOLD-DIDACTIC GMBH, Type 731-91, 0.3 kW, 220 V, 2.2 A, 2000 rpm) and a driver (SCR full-wave controlled rectifier) as shown in Fig. 3. A speed sensor (tacho-generator LEYBOLD, Type 731-09) and a low-pass filter are also conducted. The parameters of this motor plant have been identified and obtained at 1,000 rpm as follows: R_a = 54.7280 Ω, L_a = 1.5104 H, J = 36.4277 kg-m^2, B = 0.0988 N-m-sec/rad, K_t = 2.7761 N-m/A, K_b = 1.6046 V/rpm, K_A = 3.4449 and τ_A = 0.3350 sec. Very good agreement between actual speed response and the plant model can be observed in Fig. 4. The DC motor plant in (6) can be written in (7).

2.2 PID controller loop

A feedback loop of DC motor speed control with PID controller is represented in Fig. 5, where $G_p(s)$ and $G_c(s)$ are the plant and the PID controller, respectively. The model in (7) will be used as the plant $G_p(s)$ in Fig. 5. The PID controller receives error signal $E(s)$ and generates control signal $U(s)$ to control output $C(s)$ and regulate load disturbance $D(s)$ referring to referent input $R(s)$. The time-domain and s-domain functions of the PID controller are stated in (8) and (9), where K_p, K_i and K_d are the proportional, integral and derivative gains, respectively. The closed loop transfer function with PID controller is given in (10). The main purposes of control are to make the $C(s)$ tracking the $R(s)$ and simultaneously regulating the $C(s)$ whenever the $D(s)$ is applied into the control loop at T_{dist} as virtualized in Fig. 6.

$$\frac{\Omega(s)}{V_{in}(s)}=\frac{9.563}{18.43s^3+722.9s^2+1997s+9.862} \tag{7}$$

$$u(t)\big|_{PID}=K_pe(t)+K_i\int e(t)dt+K_d\frac{de(t)}{dt} \tag{8}$$

$$G_c(s)=K_p+\frac{K_i}{s}+K_ds \tag{9}$$

$$\frac{C(s)}{R(s)}=\frac{\left(K_p+\frac{K_i}{s}+K_ds\right)G_p(s)}{1+\left(K_p+\frac{K_i}{s}+K_ds\right)G_p(s)} \tag{10}$$

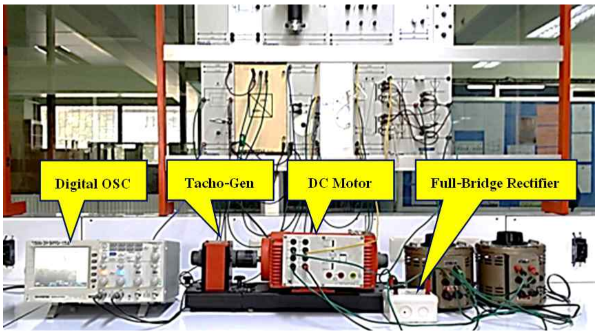

Fig. 3. DC motor plant testing rig

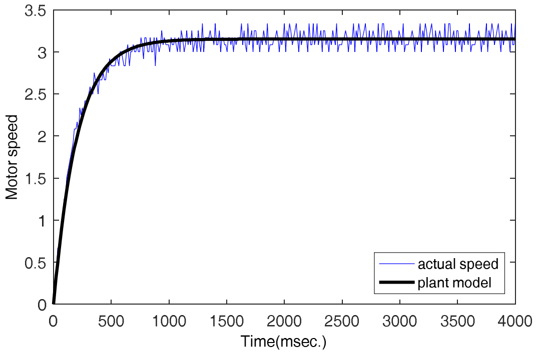

Fig. 4. Plots of actual speed response and plant model

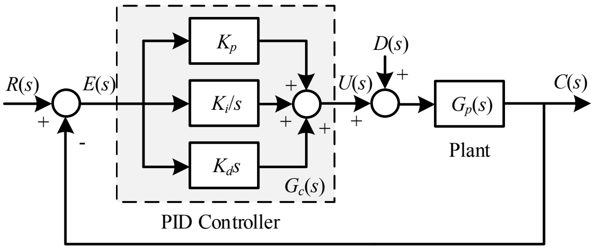

Fig. 5. PID control loop

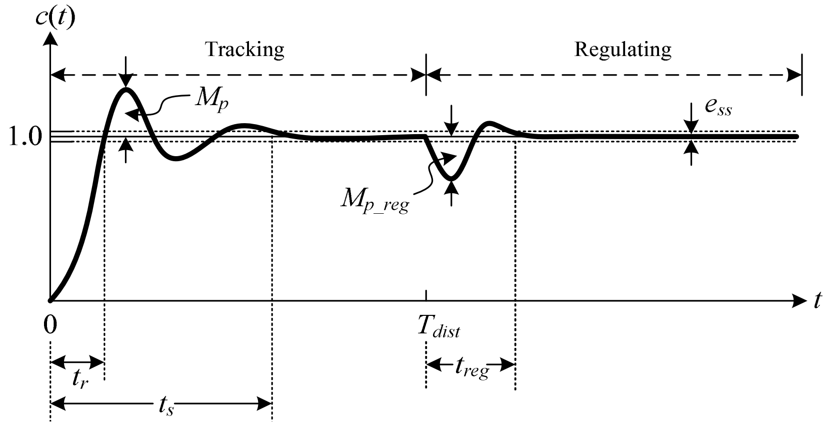

Fig. 6. Tracking and regulating purposes

2.3 PID design optimization problem

The PID controller design optimization for DC motor speed control by the CS can be represented by the block diagram in Fig. 7. The sum-squared error between $R(s)$ and $C(s)$ is set as the objective function f_{obj} expressed in (11). For command tracking purpose, rise time (t_r), maximum percent overshoot (M_p), settling time (t_s) and steady-state error (e_{ss}) are set as the inequality constraints stated in (12). For load regulating purpose, regulating time (t_{reg}) and maximum percent overshoot of load regulation (M_{p_reg}) are set as the inequality constraints also stated in (12). The PID design problem is to search for optimal parameters K_p, K_i and K_d in (11). The f_{obj} will be fed back to the CS tuning block to be minimized in order to find the optimal PID parameters satisfying to the inequality constraints as stated in (12). Referring to the inequality constraints expressed in (12), both tracking and regulating constraints are proposed together to cover two main purposes of control system design simultaneously. If the tracking part is considered, while the regulating is ignored, the command tracking response of the controlled system will be treated, but the disturbance rejection response will be unpredictable. On the other hand, if the regulating part is conducted, while the tracking is not considered, the disturbance rejection responses of the controlled system will be treated, but the command tracking response will not be guaranteed. Therefore, setting the inequality constraints with tracking and regulating as shown in (12) can guarantee both command tracking and disturbance rejection responses of the controlled system. The values of t_r, M_p, t_s, e_{ss}, t_{reg} and M_{p_reg} appeared in (12) are set from the preliminary study and simulation of this system. This is the problem-dependent of each system of interest.

$$\textbf{Min} \quad f_{obj}(K_p, K_i, K_d) = \sum_{i=1}^{N}[r(i)-c(i)]^2 \tag{11}$$

$$\text{Subject to:} \quad \left.\begin{array}{l} \left.\begin{array}{l} t_r \le 0.2 \text{ sec.} \\ M_p \le 10\% \\ t_s \le 0.5\% \\ e_{ss} \le 0.1\% \end{array}\right\} : \text{ Tracking} \\ \left.\begin{array}{l} t_{reg} \le 0.5 \text{ sec.} \\ M_{p\_reg} \le 20\% \end{array}\right\} : \text{ Regulating} \\ \left.\begin{array}{l} 0 \le K_p \le 10, \\ 0 \le K_i \le 0.1, \\ 0 \le K_d \le 4.0 \end{array}\right\} : \text{ Search spaces} \end{array}\right\} \tag{12}$$

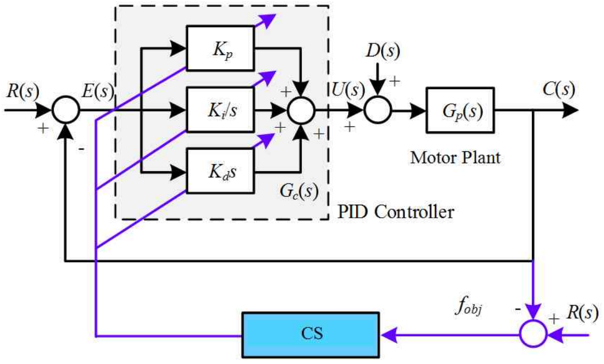

Fig. 7. CS-based PID control design optimization

3. Cuckoo Search Algorithms

In 2009, Yang and Deb proposed the cuckoo search (CS) [37] as one of the most powerful population-based metaheuristic optimization techniques. In CS algorithm, each cuckoo lays one egg at a time, and dumps it in a randomly chosen nest. The best nests with high quality of eggs (solutions) will carry over to the next generation. The number of available host nests is fixed, and a host can discover an alien egg with a probability $p_a \in [0, 1]$. The CS algorithms can be represented by the flow diagram as visualized in Fig. 8.

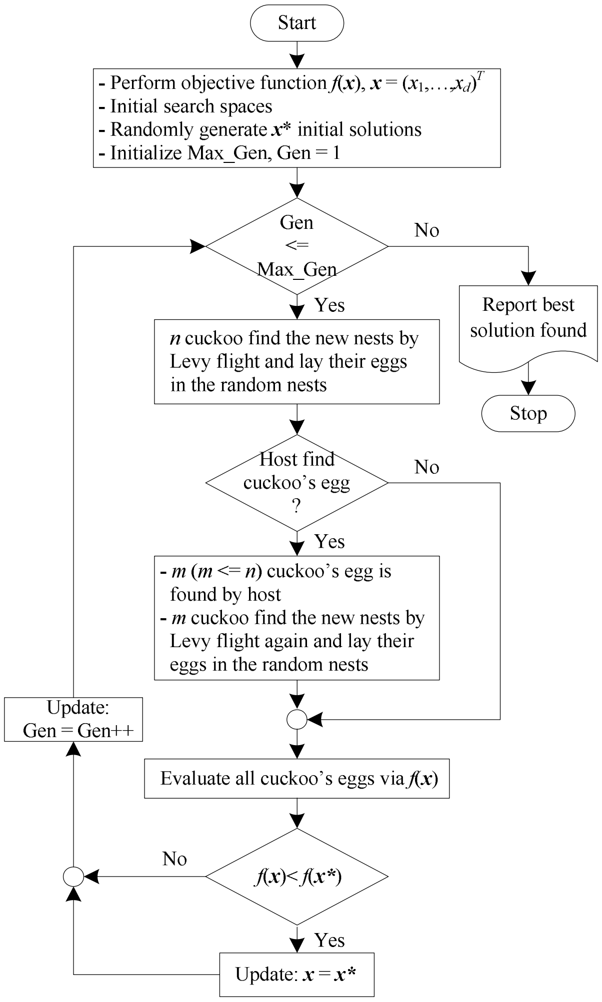

Fig. 8. Flow diagram of CS algorithms

New solutions $\boldsymbol{x}^{(t+1)}$ for cuckoo i can be generated by using a Lévy flight as stated in (13). Symbol Lévy(λ) in (13) represents a Lévy flight providing random walk with random step drawn from a Lévy distribution having an infinite variance with an infinite mean as expressed in (14), where t stands for the time. In another way, the step length s of cuckoo flight can be calculated by (15), where u and v are drawn from normal distribution as stated in (16), where N is denoted as the normal distribution. Standard deviations of u and v are also expressed in (17), where Γ is the standard Gamma function.

$$\boldsymbol{x}_i^{(t+1)} = \boldsymbol{x}_i^{(t)} + \alpha \oplus \text{Lévy}(\lambda) \tag{13}$$

$$\text{Lévy} \approx u = t^{-\lambda}, \quad 1 < \lambda \le 3 \tag{14}$$

$$s = \frac{u}{|v|^{1/\beta}} \tag{15}$$

$$u \approx N(0.\sigma_u^2) \qquad v \approx N(0.\sigma_v^2) \tag{16}$$

$$\left.\begin{aligned} \sigma_u &= \left(\frac{\Gamma(1+\beta)\sin(\pi\beta/2)}{\Gamma[(1+\beta)/2]\beta 2^{(\beta-1)/2}}\right)^{1/\beta}, 0<\beta\le 2 \\ \sigma_v &= 1 \end{aligned}\right\} \tag{17}$$

From their preliminary parametric studies, Yang and Deb provided the recommendations for users to set the search parameters of the CS for most optimization problems [37, 38, 39, 40]: the numbers of nests n = 15 to 25, α = 1.0, β = 1.5 and the probability fraction p_a = 0.25 to 0.5.

Once the CS is applied to design the PID controller for DC motor speed control system, its algorithms can be represented step-by-step to show how the CS find the optimal parameters K_p, K_i and K_d of the PID controller as follows.

Step-0 Perform the objective function f_{obj} as (11) with the inequality constraint functions as (12), the search spaces of K_p, K_i and K_d as (12), Max_Gen and Gen=1. The numbers of nests (numbers of cuckoos) = n. In this step, the initial solutions $\boldsymbol{x}^*$ (initial values of K_p, K_i and K_d) are randomly generated within the given search spaces.

Step-1 If Gen<=Max_Gen, n cuckoos find the new nests by Lévy flight in (15) associated with formulations (16) and (17) to lay their eggs in the random nests. Otherwise, report the optimal solution $\boldsymbol{x}^*$ (K_p, K_i and K_d).

Step-2 If m (m<=n) cuckoos' eggs are found by hosts, m cuckoos have to find the new nests by Lévy flight in (15) associated with formulations (16) and (17) again to lay their eggs in the random nests.

Step-3 New solutions (K_p, K_i and K_d) will be calculated via (13). Then, they are evaluated by the objective function f_{obj} in (11) and the inequality constraint functions in (12).

Step-4 If the f_{obj} with new solutions is less than the f_{obj} with old solutions, the solutions $\boldsymbol{x}^*$ (K_p, K_i and K_d) will be updated. Otherwise, the old solutions $\boldsymbol{x}^*$ are maintained.

Step-5 Update Gen= Gen+1, and go back to Step-1 to proceed the next generation.

4. Results and Disscussions

The CS is applied to design an optimal PID controller for DC motor speed control system. Referring to Fig. 7, the CS algorithms were coded by MATLAB running on Intel(R) Core(TM) i5-2430M, 2.4 GHz, 8 GB-RAM computer. The search parameters of the CS are set according to the recommendations [37-40], i.e. n =20, α =1.0, β =1.5 and p_a=0.3. Max_Gen = 100 is set as the TC. The design approach runs 100 trials with different initial solutions to obtain the best solutions (K_p, K_i and K_d). After the search process stopped, the convergent rates of the proposed objective function in (11) are depicted in Fig. 9. The optimal parameters of the PID controller are successfully obtained as stated in (18).

$$G_c(s)\big|_{PID\_CS} = 3.25 + \frac{0.03}{s} + 2.66s \tag{18}$$

For comparison, the second method of Z-N is applied in this work to design the PID controller for DC motor speed control system. Details of the Z-N design tuning rules are omitted in this article. Readers can find its more details from [12]. The PID controller designed by the second method of Z-N is then stated in (19).

$$G_c(s)\big|_{PID\_ZN} = 4{,}914.53 + \frac{16{,}284.08}{s} + 371.05s \tag{19}$$

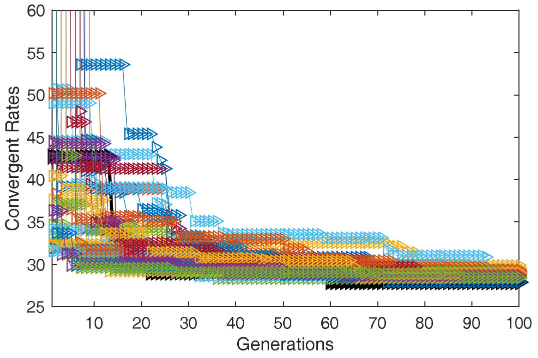

Fig. 9. Convergent rates of objective function

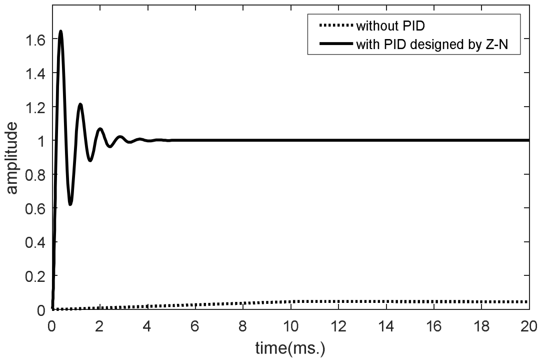

Fig. 10. Responses without and with PID designed by Z-N

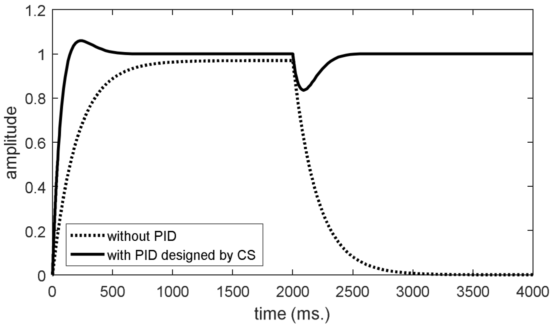

Fig. 11. Responses without and with PID designed by CS

4.1 Simulation results

The PID controllers for DC motor speed control system obtained by the second method of Z-N in (19) and the CS in (18) are conducted for simulation via MATLAB as visualized in Fig. 10 and Fig. 11, respectively. From Fig. 10, it was found that the PID controller designed by the Z-N provides very fast and very high overshoot response, i.e. t_r = 0.17 msec., t_s = 2.88 msec., M_p = 64.48% and e_{ss} = 0.00%. Once considering the controller gains in (19), it was found that the values of K_p, K_i and K_d are very great and probably cannot be realized by any hardware. This leads the PID controller designed by the Z-N impractical for implementation.

Referring to Fig. 11, it was found that the PID controller designed by the CS gives the reasonable response satisfying the inequality constraints in (12): for tracking, t_r=0.15 msec., t_s=0.42 sec., M_p=5.58% and e_{ss} = 0.00% and for regulating, M_{p_reg}=16.47% and t_{reg}=2.36 sec. These results show the main advantage of the proposed design approach and obtained responses superior to the conventional design method such as the Z-N design tuning rules. When considering the controller gains in (18), it was found that the values of K_p, K_i and K_d are possible to be realized by any hardware. This leads the PID controller designed by the CS practical for realization and implementation.

4.2 Experimental results

To confirm the simulation results, the DC motor speed control system with PID controller needs to be implemented. The DC motor control system is developed as a testing rig by using an analog technology as shown in Fig. 12 to perform the experimental results. An optimal PID controller designed by the CS is realized by op-amp LM335 and RC network to ensure real-time operation. Signal conditioning circuits including low-pass filter and zero-span circuit are also employed. The electrical load is applied for the step load disturbance input. With this scheme, the DC generator (load) is also conducted to generate the output voltage for electrical load.

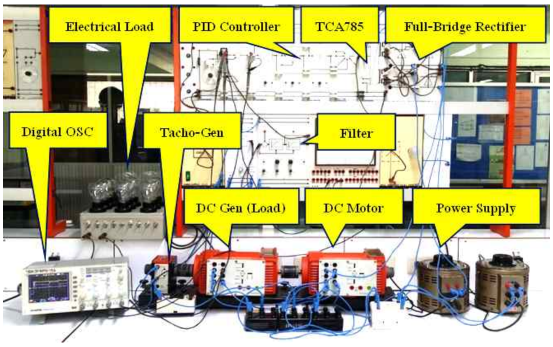

Fig. 12. DC motor speed control system testing rig

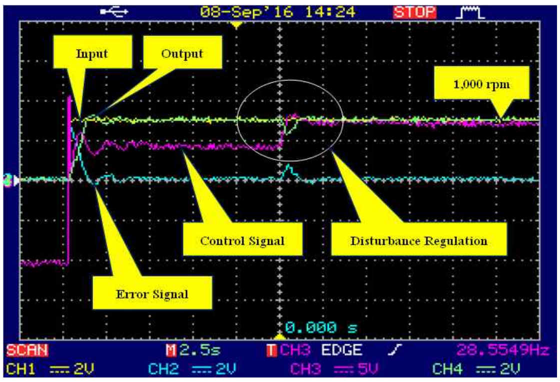

Fig. 13. System responses (experimental results)

From testing, the experimental results of the DC motor speed control system with PID controller designed by the CS are depicted in Fig. 13. The PID controller designed by the Z-N cannot be implemented due to the high values of controller gains. From Fig. 13, the system response at 1,000 rpm provides t_r=1.25 sec., t_s = 2.60 sec., M_p = 6.50%, M_{p_reg}=18.50%, t_{reg}=2.25 sec. and e_{ss}=0.00%. Once comparing to the simulation results, the system output from experimental results gives slower response. This is because of the DC generator (load) added into the system. It makes the entire time constant of the system greater. The time-delay occurred in the output response as appeared in Fig. 13 is due to the TCA785 trigger circuits and power electronic devices installed in full-bridge rectifier circuits. However, when considering the overall system response, it was found that the experimental results are corresponding to the simulation ones. Moreover, the developed system can efficiently regulate the load disturbance of 90% of motor rated.

5. Conclusions

Design of an optimal PID controller for the DC motor speed control system with tracking and regulating constrained optimization by using the cuckoo search (CS), one of the most powerful population-based metaheuristics, has been proposed in this article. Based on the modern optimization, the sum-squared error between the referent input and the controlled output has been set as the objective function, while the rise time, the maximum overshoot, the settling time and the steady-state error have been set as tracking constraints and the regulating time and the maximum overshoot of load regulation have been set as regulating constraints. As simulation results compared with the Ziegler-Nichols (Z-N) tuning rules, it was found that the Z-N provided very high gains of PID controller which cannot be realized and implemented, while the CS revealed an optimal PID controller for DC motor speed control system satisfying both tracking and regulating constraints. In this work, the simulation results have been confirmed by the experimental ones from a testing rig of DC motor speed control system developed by analog technology. For the overall system response, the experimental results are corresponding to the simulation ones. In future research, the proposed design approach will be extended to design the proportional-integral-derivative-accelerated (PIDA) controllers for real-world control systems. Moreover, the CS algorithms need some modifications in order to speed up the search process and guarantee the exactly optimal solution found in general case.

Acknowledgements

The author would like to thank the anonymous reviewers for their helpful and constructive comments that greatly contributed to improving the final version of the paper. Also, they would like to thank the Editors for their generous comments and support during the review process.

References

[1] C. L. Phillips and R. D. Harbor, Feedback Control Systems, *Prentice-Hall*, 1991.

[2] B. C. Kuo, Automatic control systems, *John Wiley & Sons*, 2003.

[3] R. C. Dorf and R. H. Bishop, Modern Control Systems, *Prentice-Hall*, 2005.

[4] K. Ogata, Modern Control Engineering, *Prentice-Hall*, 2010.

[5] J. J. Rubio, "Hybrid controller with observer for the estimation and rejection of disturbances," *ISA Transactions*, vol. 65, pp.445-455, 2016.

[6] A-I. Carlos, S-R. Hebertt and S. S-C. Miguel, "A linear active disturbance rejection control for a ball and rigid triangle system," *Mathematical Problems in Engineering*, vol. 2016, pp. 1-11, 2016.

[7] J. J. Rubio, "Sliding mode control of robotic arms with deadzone," *IET Control, Theory and Applications*, vol. 11, no. 8, pp. 1214-1221, 2017.

[8] N. Minorsky, "Directional stability of automatically steered bodies," *American Society of Naval Engineering*, vol. 34, pp. 284, 1922.

[9] A. Dwyer, Handbook of PI and PID Controller Tuning Rules, *Imperial College Press*, 2003.

[10] J. J. Rubio, P. Cruz, L. A. Paramo, J. A. Meda, D. Mujica and R. S. Ortigoza, "PID anti-vibation control of a robotic arm," *IEEE Latin America Transactions*, vol. 14, no. 7, pp. 3144-3150, 2016.

[11] P. T. Garran and G. Garcia, "Design of a PID controller for a coupled tanks system employing ADRC," *IEEE Latin America Transactions*, vol. 15, no. 2, pp. 189-196, 2017.

[12] J. G. Ziegler and N. B. Nichols, "Optimum settings for automatic controllers," *Trans. ASME*, vol. 64, pp. 759-768, 1942.

[13] G. H. Cohen and G. A. Coon, "Theoretical consideration of retarded control," *Trans. ASME*, vol. 75, pp. 827-834, 1953.

[14] V. Zakian, Control Systems Design: A New Framework, *Springer-Verlag*, 2005.

[15] V. Zakian and U. Al-Naib, "Design of dynamical and control systems by the method of inequalities," *in Proc. of the IEE International Conference*, vol. 120, pp. 1421-1427, 1973.

[16] S. Mehrdad and C. Greg, "An adaptive PID controller based on genetic algorithm processor," *in Proc. of the International Conference on Genetic Algorithm in Engineering System*, pp. 88-93, 1995.

[17] Y. Mitsukura, T. Yamamoto and M. Kaneda, "A design of self-tuning PID controller using a genetic algorithm," *in Proc. of the International Conference on American Control Conference*, pp. 1361-1365, 1999.

[18] J. F. Whidborne, "A genetic algorithm approach to design finite-precision PID controller structures," *in Proc. of the International Conference on American Control Conference*, pp.4338-4342, 1999.

[19] R. Bindu, K. Mini and K. Namboothiripad, "Tuning of PID controller for DC servo motor using genetic algorithm," *in Proc. of the International Journal of Emerging Technology and Advanced Engineering (IJETAE)*, vol. 2, no. 3, pp. 310-314, 2012.

[20] S. Srikanth and G. R. Chandra, "Modeling and PID control of the brushless DC motor with the help of genetic algorithm," *in Proc. of the IEEE International Conference on Advances in Engineering, Science and Management (ICAESM-2012)*, pp. 639-644, 2012.

[21] N. P. Adhikari, M. Choubey and R. Singh, "DC motor control using Ziegler Nichols and genetic algorithm technique," *Int. J. Electr. Electron. Comput. Eng.*, 2012.

[22] Y. Arturo, J. C. Ren, J. R. Troncoso, L. M. Velazquez and R. A. Osornio-Rios, "PID-controller tuning optimization with genetic algorithms in servo systems," *International Journal of Advanced Robotic Systems*, vol.10, pp. 324, 2013.

[23] A. T. El-Deen, A. A. H. Mahmoud and A. R. El-Sawi, "Optimal PID tuning for DC motor speed controller based on genetic algorithm," *International Review of Automatic Control* (*IREACO*), vol. 8, no. 1, pp. 80-85, 2015.

[24] A. J. Mohammed, "A particle swarm optimization

(PSO) based optimum of tuning PID controller for a separately excited DC motor (SEDM)," *Eng. & Tech. Journal*, vol. 29, no. 16, pp. 3322- 3323, 2011.

[25] H. E. A. Ibrahim and M. A. Elnady, "A comparative study of PID, fuzzy, fuzzy-PID, PSO-PID, PSO-fuzzy, and PSO-fuzzy-PID controllers for speed control of DC motor drive," *International Review of Automatic Control (IREACO)*, vol. 6, no. 4, pp. 393-403, 2013.

[26] A. Jalilvand, A. Kimiyaghalam and A. H. Kord, "Optimal tuning of PID controller parameters on a DC motor based on advanced particle swarm optimization algorithm," *International Journal on Technical and Physical Problems of Engineering (IJTPE)*, vol. 3, no. 4, pp. 10-17, 2011.

[27] A. Jalilvand, R. Aghmasheh and E. Khalkhali, "Optimal design of PID power system stabilizer in multi-machine power system using PSO and genetic algorithm," *International Review of Electrical Engineering* (*IREE*), vol. 6, no. 2, pp. 907-912, 2011.

[28] M. I. Solihin, L. F. Tack and M. L. Kean, "Tuning of PID controller using particle swarm optimization (PSO)," *in Proc. of the International Conference on Advanced Science, Engineering and Information Technology (ICASEIT2011)*, 2011.

[29] S. Bouallegue, J. Haggege, M. Ayadin and M. Benrejeb, "PID-type fuzzy logic controller tuning based on particle swarm optimization," *Elsevier journal on Engineering Applications of Artificial Intelligence*, vol. 25, no. 3, pp. 484-493, 2012.

[30] H. T. Dorrah, A. M. El-Garhy and M. E. El-Shimy, "Design of PSO-based optimal fuzzy PID controllers for the two-coupled distillation column process," *in Proc. of the International Middle East Power Systems Conference* (*MEPCON2010*), 2010.

[31] M. Nasri, N. P. Hossein and M. Maghfoori, "A PSO-based optimum design of PID controller for a linear brushless DC motor," *World Academy of Science, Engineering and Technology*, vol. 20, pp. 211-215, 2007.

[32] C. Kiree, D. Kumpanya, S. Tunyasrirut and D. Puangdownreong, "PSO-Based Optimal PI(D) Controller Design for Brushless DC Motor," *Journal of Electrical Engineering & Technology*, vol. 11, no. 3, pp. 715-723, 2016.

[33] M. Ünal, A. V. Topuz and H. Erdal, "Optimization of PID controllers using ant colony and genetic algorithms," *Springer*, 2013.

[34] H. E. A. Ibrahim and A. A. H. Mahmoud, "DC motor control using PID controller based on improved ant colony algorithm," *International Review of Automatic Control* (*IREACO*), vol. 7, no. 1, pp. 1-6, 2014.

[35] M. J. Blondin and P. Sicard, "PID controllers and anti-windup systems tuning using ant colony optimization," *Journal of Power Electronics and Applications* (*EPE*), pp. 1-10, 2013.

[36] I. Chiha, H. Liouane and N. Liouane, "A hybrid method based on multi-objective ant colony optimization and differential evolution to design PID DC motor speed controller," *International Review on Modelling and Simulations (IREMOS)*, vol. 5, no. 2, pp. 905-912, 2012.

[37] X. S. Yang and S. Deb, "Cuckoo search via Lévy flights," *in Proc. of the World Congress on Nature & Biologically Inspired Computing (NaBIC 2009)*, pp. 210-214, 2009.

[38] X. S. Yang, "Cuckoo search and firefly algorithm: overview and analysis," *Studied in Computational Intelligence: Cuckoo search and Firefly Algorithm Theory and Applications, Springer*, pp. 1-26, 2014.

[39] X. S. Yang and S. Deb, "Engineering optimisation by cuckoo search," *Mathematical Modelling and Numerical Optimisation*, vol. 1, no. 4, pp. 330-343, 2010.

[40] X.S. Yang and S. Deb, "Multiobjective cuckoo search for design optimization," *Computers and Operations Research*, vol. 40, no. 6, pp. 1616-1624, 2013.

[41] M. Kishnani, S. Pareek and R. Gupta, "Optimal tuning of PID controller by cuckoo search via Lévy flights," *in Proc. of the International Conference on Advances in Engineering and Technology Research* (*ICAETR*), 2014.

[42] R. Sethi, S. Panda and B. P. Sahoo, "Cuckoo search algorithm based optimal tuning of PID structured TCSC controller," *Computational Intelligence in Data Mining,* vol. 1, pp. 251-263, 2014.

[43] D. Puangdownreong, C. Kiree, D. Kumpanya and S. Tunyasrirut, "Application of cuckoo search to design optimal PID/PI controllers of BLDC motor speed control system," *in Proc. of the Global Engineering & Applied Science Conference*, pp. 99-106, 2015.

[44] P. C. Krause, Analysis of Electric Machinery, *McGraw-Hill Book Company*, 1983.

[45] P. C. Krause, O. Wasynczuk, S. D. Sudhoff, Analysis of Electric Machinery and Drive Systems, *IEEE Press, Piscataway*, NJ, 2002.

Deacha Puangdownreong received his B.Eng., M.Eng. and Ph.D. degrees, all in Electrical Engineering, from Southeast Asia University (SAU), Bangkok, Thailand, King Mongkut's Institute of Technology Ladkrabang (KMITL), Bangkok, Thailand and Suranaree University of Technology (SUT), Nakhon Ratchasima, Thailand, in 1993, 1996 and 2005, respectively. He is currently an associated professor of electrical engineering of Southeast Asia University, Bangkok, Thailand. His research interests include control synthesis and design, metaheuristics applications to various control engineering problems.