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Design of PID Controller for DC Motor Speed Control System with Ziegler-Nichols Method

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Abstract: Metaheuristic optimization approach has become the new framework for control synthesis. The main purposes of the control design are commanded (input) tracking and load (disturbance) regulating. This paper proposes the design of optimal proportional-integral-derivative (PID) controller for the DC motor speed control system with Ziegler-Nichols Z-N Method, one of the most efficient population-based metaheuristic optimization techniques. The sum-squared error between the reference 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 conventional design method named Ziegler- Nichols (Z-N) tuning rules. From the simulation results, it was found that the Z-N provides an impractical PID controller with very high gains.

Keywords: PID controller, Tracking,regulating, Ziegler-Nichols Z-N Method, Metaheuristics.

I. INTRODUCTION

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 the parameters of PID controller are 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 a 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), designing of the PID controller by particle swarm optimization (PSO) [7- 12] and designing of the PID controller by ant colony optimization (ACO) [3-6]. However, almost all research works considered only tracking purpose of control system design. By literatures about applications of metaheuristic techniques to optimal PID controller design as mentioned earlier, the objective functions (error between the reference 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. 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 one of the conventional design methods named Ziegler-Nichols (Z-N) tuning rules [12].

II. DESIGN OF PID

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.

A. 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[4, 5], 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, w(t) is motor speed and q(t) is motor position.

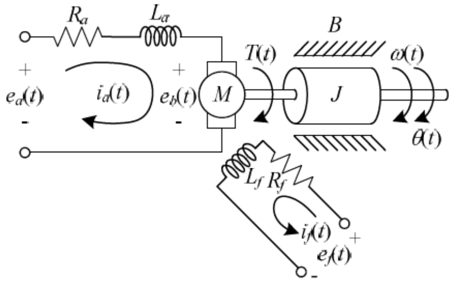

Fig.1. Schematic diagram of DC motor[7].

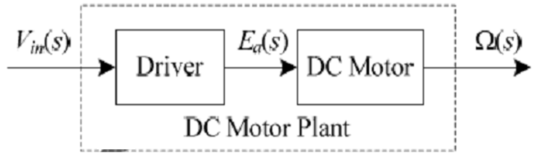

Fig.2. DC motor plant.

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, 8, 14], 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).

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

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

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

$$\frac{\Omega(s)}{E_a(s)} = \frac{K_t}{JL_a s^3+(BL_a+JR_a)s+(BR_a+K_tK_b)} \tag{4}$$

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 Fig2. The driver model is approximated by the first-order transfer function as stated in (5), where K_A is the driver gain and t_A is driver time constant. Therefore, the DC motor plant model can be rewritten as stated (6).

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

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

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). 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 W, L_a = 1.5104 H, J = 36.4277 kgm^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 t_A = 0.3350 sec. Very good agreement between actual speed response and the plant model can be observed in Fig. 3. The DC motor plant in (6) can be written in (7).

B. 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. 4. 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. 5.

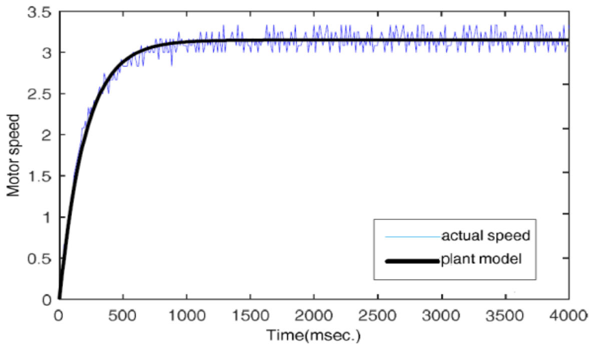

Fig.3. Plots of actual speed response and plant model.

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

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

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

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

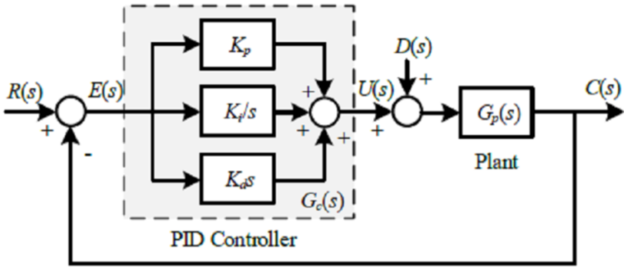

Fig.4. PID Contolar Loop.

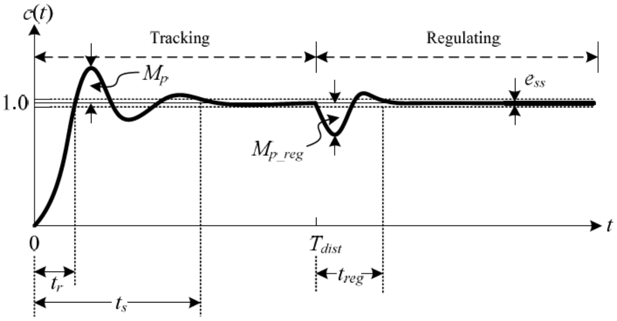

Fig.5. Tracking and regulating purposes.

C. Design of PID problem

The PID controller design optimization for DC motor speed control by the block diagram in Fig6. 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 (ts) and steady-state error (e_{ss}) are set as the inequality constraints stated in (12). For the 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).

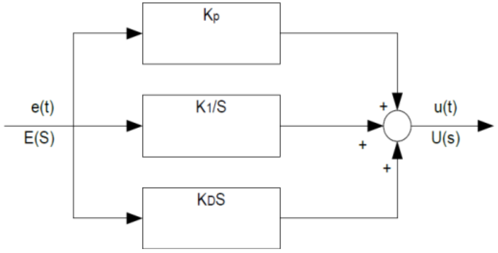

Fig.6. PID Controller Block Diagram.

The PID design problem is to search for optimal parameters K_p, K_i and K_d in (11). 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 for the preliminary study and simulation of this system. This is the problem dependent of each system of interest.

$$\text{Min } f_{obj}(k_p, k_i, k_d) = \sum_{i=1}^{N}[r(i) - c(i)]^2 \qquad (11)$$

Subject to:

$$\left.\begin{array}{l}\left.\begin{array}{r} t_r \le 0.2\text{ sec} \\ M_p \le 10\% \\ t_s \le 0.5\% \\ e_{ss} \le 0.1\% \end{array}\right\}: \text{Tracking} \\ \left.\begin{array}{r} t_{reg} \le 0.5\text{ sec} \\ M_{p_{reg}} \le 20\% \end{array}\right\}: \text{Regulating} \\ \left.\begin{array}{r} 0 \le K_p \le 10, \\ 0 \le K_i \le 0.1, \\ 0 \le K_d \le 4.0 \end{array}\right\}: \text{Search spaces} \end{array}\right\} \qquad (12)$$

III. RESULTS AND DISCUSSIONS

The 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].

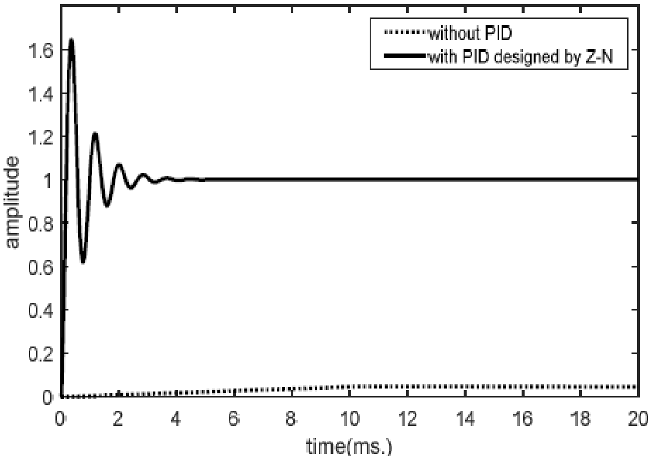

Fig.7. Responses without and with PID designed by Z-N

The PID controller designed by the method of Ziegler-Nichols (Z-N) is stated in (13).

$$G_c(s)|_{PID\_ZN} = 4{,}914.53 + \frac{16{,}284.08}{s} + 371.05s \qquad (13)$$

IV. SIMULATION RESULTS

The PID controllers for DC motor speed control system obtained by the second method of Z-N in (13) are conducted for simulation via MATLAB as visualized in Fig7, respectively. From Fig7, 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 (13), 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. 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.

V. CONCLUSION

Design of an optimal PID controller for the DC motor speed control system with tracking and regulating constrained optimization, 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 reference 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, In this work, the simulated 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.

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