An Enhanced PID Controller for Speed Control of Brushless DC Motors Based on Convex Set Optimization

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Abstract: This paper presents an enhanced PID controller design method with an internal feedback PD controller. The proposed controller structure is organized as the convex set between PID controller and PI controller with an internal PD controller. Control parameters are determined through an optimum tuning method to improve the step response characteristics in the controllable set. The new PID structure and optimum tuning algorithm are applied to the speed control of brushless direct-current (BLDC) motors. Computer simulation results show that the proposed controller is more effective in the performance of time domain by comparing with the existence tuning rules of PID controller.

Keywords: Brushless DC motor, Convex set, Optimization, PID controller.

1. INTRODUCTION

The BrushLess Direct Current (BLDC) motors are gaining grounds in the industries, especially in the areas of appliances production, aeronautics, robotics, computer peripherals, consumer and industrial automations and so on. The reason is that BLDC motors offer many advantages over the conventional brushed DC motors, including higher efficiency, reliability, higher starting torque, reduced mechanical and electrical noises, and overall reduction of electromagnetic interference (EMI).

Recently, many modern control methodologies such as nonlinear control (Hemati *et al*., 1990), optimal control (Pelczewski and Kunz, 1990), variable structure control (Lin *et al*., 1999) and adaptive control (Cerruto *et al*., 1995) are applied to the motor control systems of diverse types including BLDC. However, these approaches are either theoretically complex or difficult to implement practically (Lin and Jan, 2002).

For these issues, conventional PID controller is most commonly used in industry owing to there merits of simple structure, high efficiency and easy implementation. But the optimally tuning gains of PID controllers have been quite difficult. Yu *et al*. (2004) have presented a LQR method to optimally tune the PID gains, Lin *et al*. (2003) have proposed Genetic Algorithm based PID control, and Kuo *et al.* (2008) have proposed a novel adaptive sliding mode control with PID tuning method for a class of uncertain systems. A partical swarm optimization (PSO) method for determining the PID controller parameters for speed control of BLDC motor has proposed by Nasri *et al*. (2007), LMI method for obtaining PID controller has introduced by Dobra (2003) and Cai *et al*. (2007). And also, BLDC control system implemented with the speed control and current control has been developed for the high performance of BLDC driver based on a digital incremental PID control algorithm using AVR microcontroller (Xu *et al*., 2008).

This paper proposes an enhanced PID controller design method with an internal feedback PD controller based on Kim *et al.* (2005, 2007) for BLDC motor. The proposed controller structure is organized as the convex set between PID controller and PI controller with an internal PD controller. Control parameters are determined through an optimum tuning method to improve the step response characteristics in the controllable set. The new PID structure and optimum tuning algorithm are applied to the speed control of BLDC motors.

This paper is organized as follows: the proposed enhanced PID control scheme is presented in Section 2. The design method for tuning PID controller parameters is discussed in Section 3. BLDC motor model is reviewed in Section 4. Finally, simulation results are presented in Section 5.

2. MULTI-LOOP PID CONTROL SCHEME

Figure 1 shows the structure of an enhanced PID control system which has the inner feedback compensation.

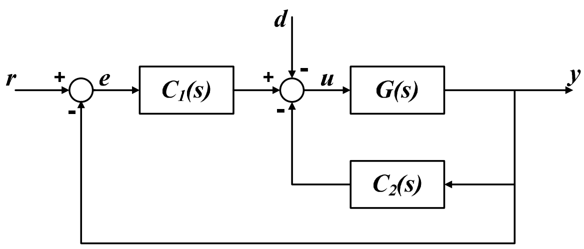

Fig. 1. Structure of Enhanced PID Control System

In Fig. 1, $G(s)$ is the uncertain plant model, $C_1(s)$ and $C_2(s)$ are the controllers, r is the reference input, u is the control command, y is the plant output, d is the disturbance signal applied to the system and e is the error defined as $e = r - y$.

The input-output relation is written in the form as

$$W_{ry}(s) = \frac{C_1(s)G(s)}{1 + \left(C_1(s) + C_2(s)\right)G(s)}. \qquad (1)$$

If $C_2(s)$ and the inner feedback loop don't exist, the above structure is equal to the conventional PID control system. In accordance with the forms of $C_1(s)$ and $C_2(s)$, the system can be represent as PID-P, PI-PD or PI-D control system, and so on. It is considered PID and PI-PD controllers in this paper.

Figure 2 shows that the structure of multi-loop control system is equivalent to 2 degree-of-freedom (DOF) control system, when the controller $C(s)$ and the prefilter $F(s)$ are

$$C(s) = C_1(s) + C_2(s), \qquad (2)$$

$$F(s) = \frac{C_2(s)}{C_1(s) + C_2(s)}. \qquad (3)$$

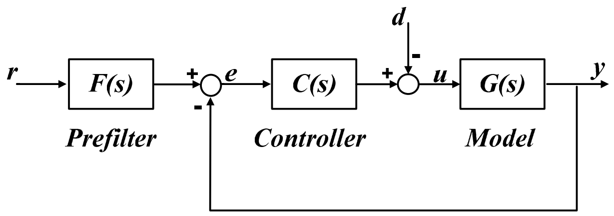

Fig. 2. Two DOF Control Systems

The transfer functions of $C_1(s)$ and $C_2(s)$ are PI controller and PD controller, respectively, as following:

$$C_1(s) = K_{p1}^*(1 + \frac{1}{T_{i1}^* s}), \qquad (4)$$

$$C_2(s) = K_{p2}^*(1 + T_{d2}^* s). \qquad (5)$$

From (2) ~ (5), controller $C(s)$ of 2 DOF systems is denoted as the PID controller

$$C(s) = K_p^*(1 + \frac{1}{T_i^* s} + T_d^* s), \qquad (6)$$

where

$$K_p^* = K_{p1}^* + K_{p2}^*, \qquad (7)$$

$$T_i^* = \frac{(K_{p1}^* + K_{p2}^*)T_{i1}^*}{K_{p1}^*}, \qquad (8)$$

$$T_d^* = \frac{K_{p2}^* T_{d2}^*}{(K_{p1}^* + K_{p2}^*)} \qquad (9)$$

and prefilter $F(s)$ is

$$F(s) = \frac{K_{p1}^*(T_{i1}^* s + 1)}{T_{i1}^* K_{p2}^* T_{d2}^* s^2 + T_{i1}^*(K_{p1}^* + K_{p2}^*)s + K_{p1}^*}. \qquad (10)$$

And also, the transfer functions of $C_1(s)$ and $C_2(s)$ is PID controller and PD controller, respectively, as following:

$$C_1(s) = K_{p1}(1 + \frac{1}{T_{i1} s} + T_{d1} s), \qquad (11)$$

$$C_2(s) = K_{p2}(1 + T_{d2} s) \qquad (12)$$

and the traditional PID controller means that

$$C_1(s) = K_p(1 + \frac{1}{T_i\ s} + T_d\ s), \qquad (13)$$

$$C_2(s) = 0. \qquad (14)$$

We will disregard the derivation of the controller $C(s)$ and the prefilter $F(s)$ for the respective PID-PD and PID controller because it can be derived from (2) ~ (3) easily.

3. CS-BASED PID-PD PARAMETER DESIGN

3.1 Convex Set of Linear Control System

In geometry of design specifications, H denotes the set of all closed-loop transfer matrices which is satisfying design specifications D and H denotes one element of transfer matrices set H. We think of H as the set of all conceivable candidate transfer matrices for the given plant. With each design specification D_i we associate the set H_i of all transfer matrices that satisfy it:

$$\mathrm{H}_i = \{H \in \mathrm{H} \mid \mathrm{H} \text{ satisfies } \mathrm{D}_i\}. \qquad (15)$$

Table 1. Properties of design specifications and the corresponding sets of transfer matrices.

Design specifications	Sets of transfer matrices
H satisfies D	$H \in \mathrm{H}$
D_1 is stronger than D_2	$\mathrm{H}_1 \subseteq \mathrm{H}_2$
D_1 is weaker than D_2	$\mathrm{H}_1 \supseteq \mathrm{H}_2$
$\mathrm{D}_1 \wedge \mathrm{D}_2$	$\mathrm{H}_1 \cap \mathrm{H}_2$
D_1 is infeasible	$\mathrm{H}_1 = 0$
D_1 is feasible	$\mathrm{H}_1 \neq 0$

According the definition 1 of affine, a set of transfer matrices is affine if, whenever an affine combination of two distinct transfer matrices is in the set including these transfer matrices.

***Definition 1**: $\mathrm{H}_1 \subseteq \mathrm{H}$ is affine if for any $H, \widetilde{H} \in \mathrm{H}_1$, and any $\lambda \in R$, $\lambda H + (1-\lambda)\widetilde{H} \in \mathrm{H}_1$*, where if λ is restricted within $[0,1]$, the affine combination $\lambda H + (1-\lambda)\widetilde{H}$ is in the convex set.