Proceedings of the 35th Chinese Control Conference
July 27-29, 2016, Chengdu, China

Angular Speed Control of Brushed DC Motor Using Nonlinear Method: Design and Experiment

ZHANG Sen[2], GU Wanli[2], HU Yunfeng[1,2], DU Juan[3], CHEN Hong[1,2]

1. State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun Jilin 130012 China

2. Department of Control Science and Engineering, Jilin University, Changchun Jilin 130025 China

3. Computing Center of Jilin Province, Changchun Jilin 130025 China

Abstract: The major concentration of this study is on developing a novel control system with response and tracking accuracy features capable of precise angular speed regulation of brushed DC motor. Towards this objective, speed loop controller of brushed DC motor based on Triple-step nonlinear method has been designed. The Triple-step nonlinear method consists of the steady-state control, the reference variation-based feed-forward control, the error feedback control. The designed nonlinear controller has the advantage of concision and specific signification. The controller can greatly enhance the transient response performance of brushed DC motor. When a brushed DC motor running at low angular speed, the system appears the speed fluctuation and dead-zone characteristic. Therefore, the friction model of motor is considered in the design of controller. Current dynamic is neglected due to the fast electric response, the commonly used feedforward controller and PI feedback controller is designed. The effectiveness of the control method compared with conventional PID controllers is verified through experiments.

Key Words: Brushed DC Motor, Triple-step Method, Friction model, Angular Speed Control

1 Introduction

Brushed DC motors have great torque coefficient, strong overload capacity, high reliability advantages, are widely used in motion tracking control of wheeled mobile robots and spacecraft ground mobile base[1]. Wheeled mobile robot drive motor control system is the executive body of the mobile robot, the motor control system plays a vital role for the smooth and rapid operational of the robot system. The speed tracking performance of driving motor will directly affect the mobile robot motion tracking effect. Thus, drive motor need to track the desired angular speed quickly and accurately in high-precision tracking control of wheeled mobile robot. However, when a brushed DC motor running at low angular speed, system will appear movement which is not smooth phenomenon, due to the friction torque. Steady state error, occurrence of instability and limit cycle oscillation may be possible due to existence of friction torque[2][3]. Effect of friction torque on the dynamic performance of the system represents waveform distortion through the zero point at low angular speed.

Currently, many experts and scholars have proposed different characteristics brushed DC motor speed control methods. PID control due to its simplicity and high reliability are widely used in brushed DC motor speed control, but PID control can not overcome the impact of speed control of nonlinear friction control[4][5]. In servo control friction compensation has been the subject in many recent studies. An important problem in friction compensation is that this force varies with temperature, normal forces, position, and so on. In [6], X.K.Wang et al. studies the dual-loop motor control system, and uses simulation optimization methodology to design of PID controller parameters, which make the dynamic and the steady-state characteristic of the control system reach the design requirements. In [7], in order to minimize the dead-zone characteristics, J.Z.Peng et al. used the Wiener-type neural network acting as a forward identifier which provides the DC motor system dynamic performance in realtime to facilitate adaptive control of the system. This combination provides an effective solution of enhancing the control performance of traditional PID controllers. But study remain in the simulation stage. In [8], Y.Y.Yang et al. proposed an adaptive robust control method based on an extended disturbance observer for motion control of DC motor which obtained an excellent high-precision performance through simulation. In[9], an backstepping-based output feedback controller has been designed for brushed DC motor servo valves. The friction has been compensated by dynamic adaptive laws. By utilizing observers, current and friction states are obtained. The performance of the controller has been verified in simulation and experiments using different reference.

This paper will use the Triple-step nonlinear method to design an angular speed controller for a Brushed DC motor. The control scheme takes three parts into account: the steady-state control, the feed-forward control related to the reference variation and the error feedback control[10]. Overlooking the whole procedure, the controller design is deduced step by step, after extracting some of the system nonlinearities by the steady-state control and feed-forward control, an explicit and affine expression of the error dynamics is obtained that simplifies the design of error feedback significantly. Such controller can significantly enhance the control performance of the motor. In the design of nonlinear controller using the triple-step nonlinear method, consider the friction torque model to compensate nonlinear phenomena at low angular speed. There are many studies on friction model, such as Coulomb friction model, Static Coulomb Viscous friction model, Stribeck friction model and so on[11]. In this paper, Stribeck friction model is considered as the friction model of Brushed DC motor. Experiment results verify the practicability and effectiveness of the nonlinear controller comparing with conventional PID controllers.

This work is supported by National Natural Science Foundation (NNSF) of China(No.61374046; 6151001021), and the 973 Program (No.2012CB821202).

Corresponding author: Chen Hong(chenh@jlu.edu.cn)

2 Brushed DC motor model

In this paper, the simplified mathematical model of the brushed DC motor is shown as following:

$$\dot{i} = -\frac{i}{L}R - \frac{Ke}{L}\omega + \frac{u}{L} \tag{1}$$

$$\dot{\omega} = \frac{K_m}{J}i - \frac{1}{J}T_L - \frac{1}{J}T_f \tag{2}$$

where T_f describe friction model. Among the friction model, Stribeck model can describe the relationship between speed and friction torque more accurately. Thus, in order to obtain better control performance in the process of design controller, Stribeck model is a better choice. Stribeck model is as follows:

$$T_f = [T_c + (T_s - T_c)\mathrm{e}^{-(\omega/\omega_s)^2} + B\omega]sgn(\omega) \tag{3}$$

Wherein, the parameters T_c, T_s, ω_s, B can be determined experimentally. The description of the symbols in the formula are shown in Table 1.

Table 1: The description of the symbols

Symbol	Significance
i	armature current A
L	equivalent inductance of armature H
R	armature equivalent resistance Ω
K_e	voltage coefficient $V \cdot s/rad$
ω	angular velocity rad/s
u	terminal voltage of armature circuit V
K_m	torque coefficient $N \cdot m/A$
J	the inertia moment of the rotor $kg \cdot m^2$
T_l	load torque $N \cdot m$
T_f	friction torque $N \cdot m$
T_d	disturbance torque $N \cdot m$
T_c	Coulomb friction torque $N \cdot m$
T_s	static friction torque $N \cdot m$
ω_s	critical Stribeck speed rad/s
B	viscous friction coefficient $N \cdot m/rad/s$

In value, the voltage coefficient K_e is much smaller than the torque coefficient K_m, therefore it can be considered the current loop and the speed loop decoupling. Using cascade control for DC motor angular speed control is feasible. In this paper, the controller of speed loop and current loop design respectively. In the industry,the brushed DC motor control strategy based on current loop and speed loop are often used.

3 CONTROL SCHEME

In order to improve the control performance of the brushed DC motor, the brushed DC motor control strategy based on the Triple-step nonlinear method is proposed. The overall system block diagram shown as: Triple-step nonlinear controller is used to compensate for the effects of nonlinear friction and suppression system deviation. Triple-step nonlinear method can be formalized as a triple-step procedure:

1) the steady-state control;
2) the reference variation-based feed-forward control;
3) the error feedback control.

The steady-state control ensure the system in a small deviation in regulation in the process of reaching steady-state. In order to obtain a better control performance, the reference variation-based feed-forward control should be considered. The reference variation-based feed-forward control can give the control amount according to the change of the reference signal. Thus, the reference variation information can improve the transient response performance. The error feedback control are utilized for suppressing deviation, improving the robustness of the system[12].

A.The controller design of speed loop

Considering the no-load condition, the state equation of speed loop as follow:

$$\dot{\omega} = \frac{K_m}{J}i - \frac{1}{J}T_f \tag{4}$$

Step 1:the steady-state control

Assumes that the system has reached steady state, the steady state control input is $i = i_s$. According to the stead state condition, by letting $\dot{\omega} = 0$ we obtain a steady-state-like control as follows:

$$K_m i_s - T_f = 0 \tag{5}$$

Then, we have

$$i_s = \frac{[T_c + (T_s - T_c)\mathrm{e}^{-(\omega/\omega_s)^2} + B\omega]sgn(\omega)}{K_m} \tag{6}$$

Step 2:the reference variation-based feed-forward control

In order to reflect the system has a corresponding regulation when the speed reference value changes dynamically, on the basis of the steady-state-like control, by setting the control law is$i = i_s + i_f$. Substituting into (4)leads to:

$$J\dot{\omega} = K_m(i_s + i_f) - T_f \tag{7}$$

Simplifying (7) we get:

$$J\dot{\omega} = K_m i_f \tag{8}$$

By letting $\dot{\omega} = \dot{\omega}^*$, (8)becomes :

$$i_f = \frac{J\dot{\omega}^*}{K_m} \tag{9}$$

Step 3:the error feedback control

In order to improve the control performance of the control system, as well as disturbance and uncertainty robustness. We introduce a feedback control u_e in the above design process. Assume that the control law is $i = i_s + i_f + i_e$, and the tracking error is defined as $\omega_e = \omega^* - \omega$. We have:

$$J\dot{\omega} = K_m(i_s+i_f+i_e)-[T_c+(T_s-T_c)\mathrm{e}^{-(\omega/\omega_s)^2}+B\omega]sgn(\omega) \tag{10}$$

Simplifying the formula we get:

$$J\dot{\omega}_e = -K_m i_e \tag{11}$$

In order to analysis the stability of the system, set Lyapunov function

$$V = \frac{1}{2}J{\omega_e}^2 + \frac{1}{2}k_1{\chi_\omega}^2 \tag{12}$$

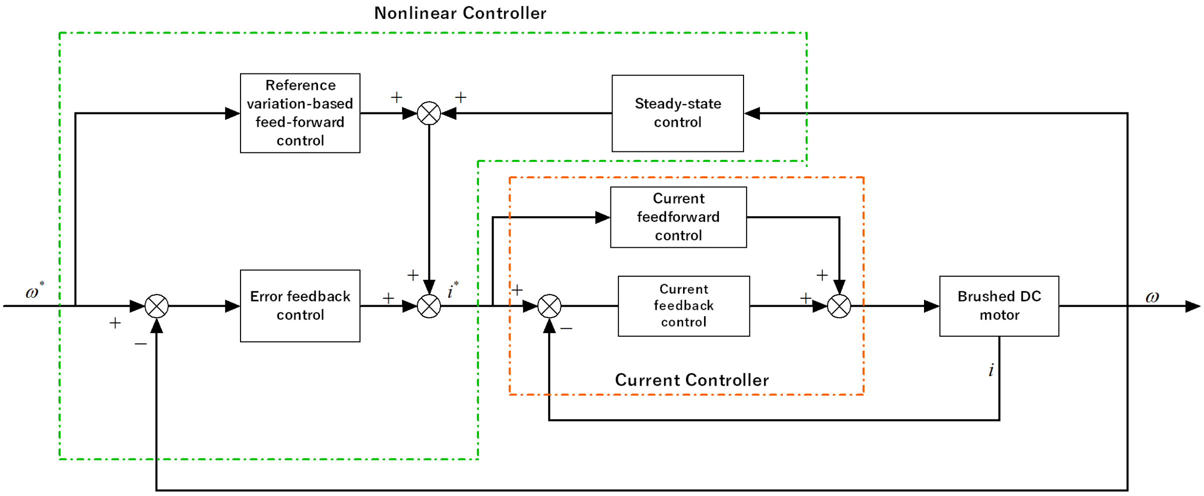

Fig. 1: The system control diagram

with $\chi_\omega = \int \omega_e$ Therefore we get:

$$\begin{aligned} \dot{V} &= J\omega_e\dot{\omega}_e + k_1\omega_e \int \omega_e \\ &= -K_m i_e \omega_e + k_1 \omega_e \int \omega_e \end{aligned} \tag{13}$$

We choose $K_m i_e = k_0\omega_e + k_q \int \omega_e$,with $k_0, k_1 > 0$. Substituting into (13), we have:

$$\dot{V} = -k_0\omega_e^2 \tag{14}$$

Through the above derivation we get a total speed loop control law:

$$i_n = i_s + i_f + i_e \tag{15}$$

$$= \frac{J\dot{\omega}^*}{K_m} + \frac{T_f}{K_m} - \frac{K_0\omega_e}{K_e} - \frac{K_1}{K_e}\int \omega_e \tag{16}$$

B.The controller design of current loop

the state equation of current loop as follow:

$$\dot{i} = -\frac{i_d}{L}R - \frac{k_e}{L}\omega + \frac{u}{L} \tag{17}$$

Step 1:the steady-state control

We suppose that the current has reached a steady state and the input of steady-state control is $u = u_s$. According to the steady-state condition, we set $\dot{i} = 0$. By substituting it into (17), we get:

$$u_s = iR + K_e\omega \tag{18}$$

Step 2:the reference variation-based feed-forward control

In order to reflect the system has a corresponding regulation when the current reference value changes dynamically, on the basis of the steady-state-like control, by setting the control law is $u_d = u_s + u_f$. Substituting into (17) leads to:

$$\dot{i} = -\frac{i}{L}R - \frac{k_e}{L}\omega + \frac{u_s + u_f}{L} \tag{19}$$

By substituting (18)into (19), we have :

$$\dot{i} = \frac{u_s}{L} \tag{20}$$

By setting $i = i^*$, we get:

$$u_s = L\dot{i}^* \tag{21}$$

Step 3:the error feedback control

In order to improve the control performance of the control system, as well as the robustness of the control system to disturbance and uncertainty. We introduce a feedback control u_e in the above design. In order to achieve a minimum deviation adjustment, the tracking error is defined as $i_e = i^* - i$. We have:

$$L\dot{i}_e = u_s + u_f + u_e - Ri - K_e\omega \tag{22}$$

Simplifying the formula we get:

$$L\dot{i}_e = u_e \tag{23}$$

In order to analysis the stability of the system, set Lyapunov function

$$V = \frac{1}{2}i_e^2 + \frac{1}{2}K_0\int i_e^2 \tag{24}$$

Therefore we get:

$$\dot{V} = i_e\dot{i}_e + K_0\chi_i \tag{25}$$

with $\chi_i = \int i_e$. We choose $u_e = -K_{i1} i_e - K_{i0} \int i_e$, with $K_{i1}, K_{i0} > 0$. Substituting into (25), we have:

$$\dot{V} = -K_1 i_e^2 \tag{26}$$

Through the above derivation we get a total current loop control law:

$$u = u_s + u_f + u_e = iR + K_e\omega - K_1 i_e - K_0 \int i_e \tag{27}$$

4 Experimental Verification

4.1 Mechanical structure and Electronic structure

To verify the validity of the above control method designed to brushed DC motors, a rapid prototyping experimental platform for brushed DC motor based on MicroAutoBox is established as shown in Fig. 2. The set of DC motors test-bed includes a permanent magnet brushed DC motor and inertial load. The DC motor and inertial load are connected coincidentally by flexible aluminum couplings. A 65536 pulse/rev high-precision shaft encoder is connected to the same shaft of the DC motor as the speed feedback. To measure DC motors' armature currents, closed loop multi-range Hall-effect based linear current sensor is used whose performance specification is measurement range of 20 amperes, analog voltage output and sensitivity of 104.16 millivolts/ampere. The impulse signal output of the encoder and the analog voltage output of the current sensor is sampled by a readily available commercial embedded real-time computer, the MicroAutoBox from dSPACE. The motor control algorithm were implemented in the MicroAutoBox. The parameters of DC brushed motor used in the experiment are as follows:

Table 2: The parameters of brushed DC motor

Parameter	Value
maximum no-load speed	$733r/min$
peak stall current	$12A$
rated voltage	$12V$
peak stall torque	$1.5N.m$
armature equivalent resistance	1Ω
torque coefficient	$0.125N.m/A$
voltage coefficient	$0.01V/r.min^{-1}$

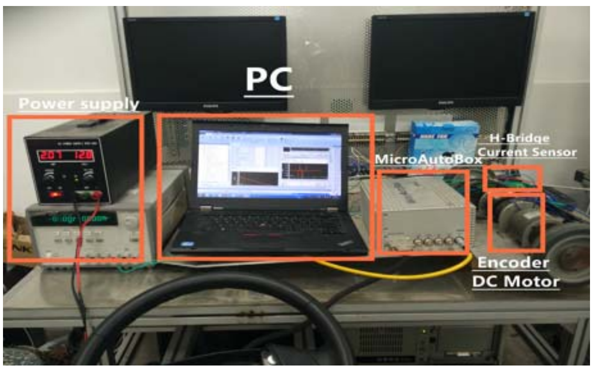

Fig. 2: Test bench

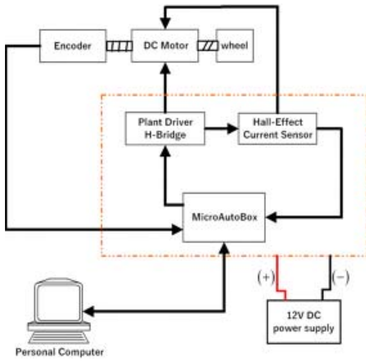

Fig. 3: Schematic block diagram

4.2 Comparative Experiment and Analysis

(1)Comparing the method of this paper with the conventional PI closed loop control method. In this experiment, the reference value of angular speed is a magnitude of $30rad/s$ step signal. In Fig. 4, we can see that the conventional PI closed loop control method track the reference angular speed about 5 seconds. But the Triple-step nonlinear method can track the reference angular speed in about 1 second. Thus the method of this paper has better transient response characteristics.

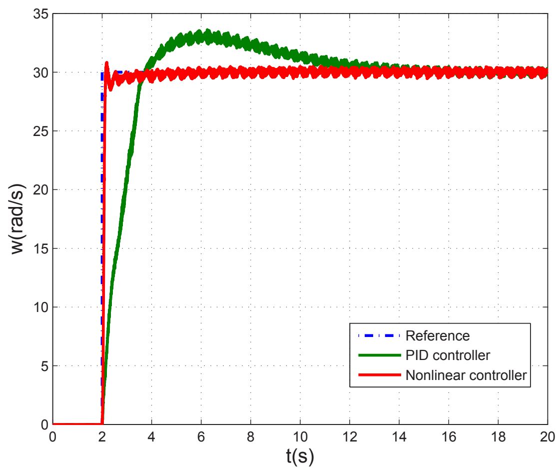

Fig. 4: Step signal response

(2)In order to verify the proposed method for the tracking ability of sinusoidal signal, we conduct experiment and compare with the conventional PI closed loop control method. In this experiment, the reference of angular speed is sinusoidal signal $\omega^*(t) = 30\sin(2\pi t)(rad/s)$ in Fig. 5 and $\omega^*(t) = 4\sin(2\pi t)(rad/s)$ in Fig. 6. Fig. 5(a) and Fig. 6(a) use the conventional PI controller. In Fig. 5(b) and in Fig. 6(b) use the nonlinear control method in this paper. When the motor speed through the zero point(motor rotation transformation), due to lower motor speed, there is a clear dead zone phenomenon when the conventional PI is used. But the Triple-step nonlinear method can lead to a smooth transition in the zero crossing. When the amplitude of reference angular speed is low, the motor has serious dead zone phenomenon. The conventional PI closed loop control method has a great tracking error and poor control effect. However, the Triple-step nonlinear method has better signal tracking effect.

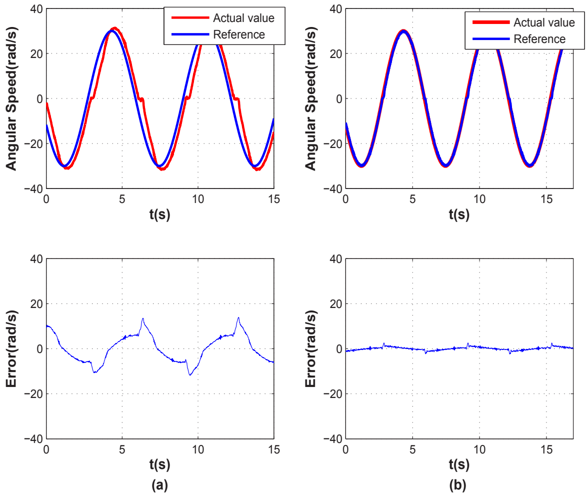

Fig. 5: the comparative of tracking effect in the reference speed of $\omega^*(t) = 30\sin(2\pi t)(rad/s)$

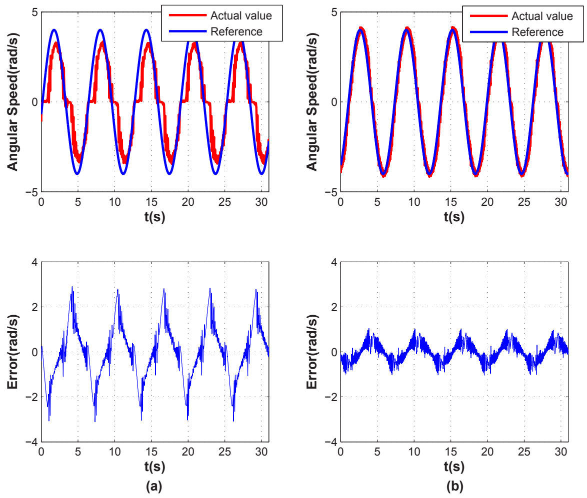

Fig. 6: the comparative of tracking effect in the reference speed of $\omega^*(t) = 4\sin(2\pi t)(rad/s)$

(3)In order to verify the proposed method for the steady tracking ability of low angular speed, we conduct experiment and compare with the conventional PI closed loop control method. In this experiment, the reference speed is $1rad/s$ and $4rad/s$. In Fig. 7(a) and Fig. 8(a), the conventional PI closed loop control method in the steady low angular speed has a great tracking error. There is a great tremble when the reference angular speed is $1rad/s$, and the peak error close to 100%. The peak error is about 12.5% when the reference angular speed is $4rad/s$. The error is low using the Triple-step nonlinear method in Fig. 7(b) and Fig. 8(b). The peak error is about 38%, when the reference angular speed is $1rad/s$. The peak error is about 3.75%, when the reference angular speed is $4rad/s$. Thus, we can see that the proposed method has good friction torque compensation capability.

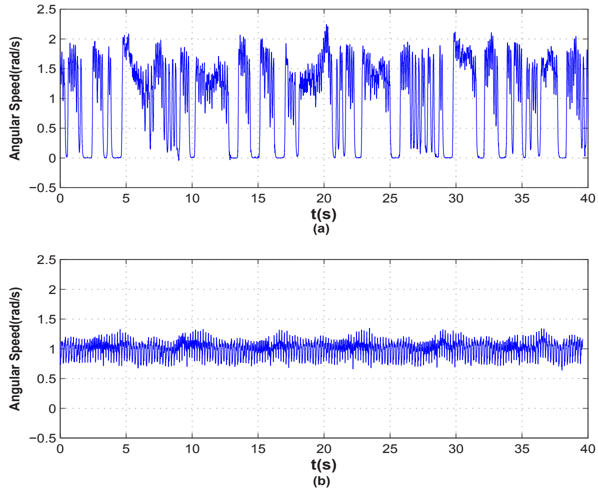

Fig. 7: the comparative of tracking effect in the steady reference speed of $1rad/s$

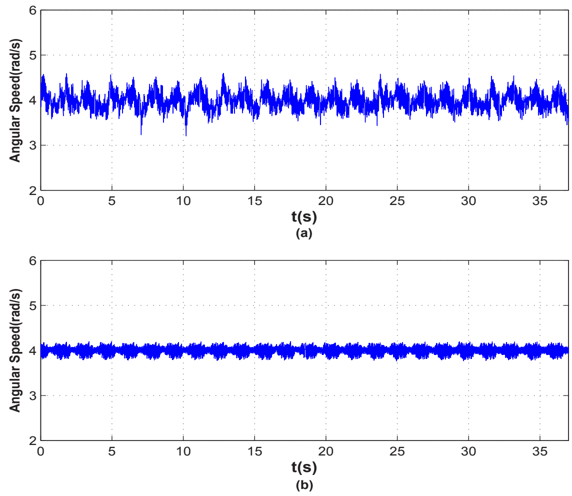

Fig. 8: the comparative of tracking effect in the steady reference speed of $4rad/s$

5 CONCLUSION

In this paper, a novel speed control algorithm based on triple-step method is introduced. The controller based on the Triple-step nonlinear method enhance the transient response characteristics effectively. Friction torque model is introduced in the design of the Triple-step process in order to compensate the friction torque disturbance. The Triple-step nonlinear method can overcome the brushed DC motor in the low speed nonlinear phenomena. Experiment results demonstrate the effectiveness and applicability of the method in this paper.

References

[1] J.Ruiz, E. Torres, E. Villarreal. Design and Construction of a Mobile Robot with Regenerative Brake on Dc Motors, *International Journal of Materials Science and Engineering*,2(1):6-9,2014.

[2] Y. Liu, J. Zhao, M. Xia, Model reference adaptive control-based speed control of brushless DC motors with low-

resolution Hall-effect sensors, *IEEE Transactions on Power Electronics*, 29(3): 1514-1522, 2014.

[3] D. Hoshino, N. Kamamichi, J Ishikawa. Friction compensation using time variant disturbance observer based on the LuGre model, *2012 12th IEEE International Workshop on Advanced Motion Control (AMC)*,2012: 1-6.

[4] O. Montiel, R. Sepulveda, P Melin. Performance of a simple tuned fuzzy controller and a PID controller on a DC motor, *IEEE Symposium on Foundations of Computational Intelligence*, 2007: 531-537.

[5] S. Sheel, O. Gupta, High performance fuzzy adaptive PID speed control of a converter driven DC motor, *International Journal of Control and Automation*, 5(1): 71-88, 2012.

[6] X. Wang, Z. Sun, L. Wang, Simulation and optimization of parameters on DC motor double closed-loop control system based on simulink, *International Conference on Intelligent Human-Machine Systems and Cybernetics*, 2009: 153-155.

[7] J. Peng, R. Dubay, Identification and adaptive neural network control of a DC motor system with dead-zone characteristics, *ISA transactions*, 50(4): 588-598, 2011.

[8] Y. Yang, Y. Wang, P. Jia. Adaptive robust control with extended disturbance observer for motion control of DC motors, *Electronics Letters*, 51(22): 1761-1763, 2015.

[9] F. S. Ahmed, S. Laghrouche, M. Harmouche, Adaptive backstepping output feedback control of DC motor actuator with friction and load uncertainty compensation, *International Journal of Robust and Nonlinear Control*, 25: 1967-1992, 2015.

[10] H. Chen, X. Gong,Q. Liu, Triple-step method to design nonlinear controller for rail pressure of gasoline direct injection engines, *IET Control Theory & Applications*, 8(11): 948-959, 2014.

[11] B. Rashidi, M. Esmaeilpour,M. R. Homaeinezhad, Precise angular speed control of permanent magnet DC motors in presence of high modeling uncertainties via sliding mode observer-based model reference adaptive algorithm, *Mechatronics*, 28: 79-95, 2015.

[12] B. Gao, H. Chen, Q. Liu, Position control of electric clutch actuator using a triple-step nonlinear method, *IEEE Transactions on Industrial Electronics*, 61(12): 6995-7003, 2014.