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Research of Auto-disturbance-rejection Controller in Motor Control System

Qiaoling Yang[1], Guangqing Bao[1] and Haiping Zhang[2]

[1]*College of Electrical and Information Engineering, Lanzhou University of Technology,LanZhou 730050, China*
[2]*Tianhua Research Institute of Chemical Machinery and Automation, LanZhou, 730050, China*
winds-qiaoer@163.com, hapi1009@163.com

Abstract

Auto-disturbance-rejection control (ADRC) technology is nonlinear robust control technology. Its nonlinear feedback relies on the size and direction of the error between desired and the actual trajectory. When the controlled object is disturbed by uncertain factor or its parameters change, ADRC can transform nonlinear system into an integral series structure of linear system by using nonlinear transformation, what can realize feedback linearization of dynamic system and improve system's control performance. According to above, we propose to apply ADRC technology to brushless DC motor control system to restrain torque ripple and improve system's disturbance-rejection in this paper. After theoretical analysis the feasibility of this method, we made a simulation. Simulation results show that the effects of torque ripple suppression and anti disturbance ability of the system have been improved.

Keywords: *auto-disturbance-rejection, controller, model, robustness, brushless DC motor, torque ripple*

1. Introduction

Currently dominant controller in motor control system is still the classical PID controller. It relies on the error between the control target and actual value to determine how to eliminate the error. It has advantages of simple principle, convenient use and strong adaptability. But it also has many shortcomings such as the control rules is a proportional, integral, differential linear combination of error, what is prone to cause contradiction between the quickness and overshoot;

$$u(t) = K_P e(t) + K_I \int_0^t e(\tau) d\tau + K_D \frac{de(t)}{dt} \tag{1}$$

Actual differentiator is replaced by first order inertia ahead links, these sectors amplify the noise signal, and resulting in differential signal can't be used; Let unsmooth input signal as a target of the output will result in oscillations and overshoot; The integral action increased the instability of the system, may also cause the integral saturation.

According to above, some people proposed three corresponding improvement measures to remedy classic PID controller [1]. The first is arranging suitable transition process; the second is extracting differential reasonable; the third is find suitable combination method. It is the prototype of auto-disturbance-rejection control (ADRC) technology.

Paper [2] has introduced theoretical basis and application value in detail of ADRC from its development to application status. ADRC is a new technology, which has improved inherent

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defects of classic PID and inherited its advantages. It is tireless exploration result of a series of fundamental problems in linear and nonlinear, model theory and cybernetics etc in feedback system. Its core is to estimate and compensate a system's total disturbance, which including un-modeled dynamic factors of the system and the unknown external disturbance by making full use of the special effect of the "non-linear" [3]. A large number of simulation experiments show that ADRC controller has wide parameters adaptability and simple algorithm. It can automatically detect and compensate for the control object within and outside disturbance [4]. When the controlled object is disturbed by uncertain factor or its parameters change, we also can get good control results. ADRC has strong adaptability, robustness, operability and the versatility in a certain type of object [5-7]. Nowadays, research about application of ADRC technology in many aspects is being carried out. ADRC applied research in the field of motor control has just started.

In this paper, we propose to apply ADRC technology to brushless DC motor control system to restrain torque ripple and improve system's disturbance-rejection. Simulation results show that the effects of torque ripple suppression and anti disturbance ability of the system have been improved. Section 2 provides the mechanism of ADRC and its simulation results. Section 3 presents the BLDCM control system based on ADRC. Section 4 presents the validation of the proposed method using experimental results. Section 5 presents the conclusions and Section 6 presents the proposed future work on this method.

2. Theoretical Analysis and Simulation of ADRC

2.1. Auto-disturbance-rejection Controller

Auto-disturbance-rejection controller is composed of tracking differentiator (TD) [8], extended state observer (ESO) [9] and nonlinear state error feedback(NLSEF) [10]. Its core is the ESO.TD arrange the transition process, ESO is used to estimate state, model and external disturbance of the system. In other words, the use of ESO is to extract information, which is need when realize state feedback or compensate external disturbance and model error [11]. The system's model and the external disturbance lies on equal standing, their real time value can be estimated and compensated by ESO. ADRC can transform nonlinear and uncertain controlled object into an integral series structure of linear system by using NLSEF. It is Feedback linearization of nonlinear uncertain object [12,13]. Feedback linearization is relying on dynamic estimations of ESO, rather than on the accurate mathematical model of the object. So you can say that it is a dynamic feedback linearization method, or a nonlinear controller independent from system's model and external disturbance.

The following is a nonlinear uncertain object disturbed by unknown external disturbance:

$$\begin{cases} x^{(n)} = f(x, x^{(1)}, \cdots, x^{(n-1)}, t) + w(t) + bu \\ y = x(t) \end{cases} \tag{2}$$

Where $f(x, x^{(1)}, \cdots, x^{(n)}, t)$ is unknown function, $w(t)$ is unknown external disturbance, $x(t)$ is measurement input, u is system's input and b is coefficient of u .

We can design the ADRC for the object after selecting appropriate non-linear function, constructing extended state observer and using nonlinear state error feedback. Corresponding ADRC controller's structure is shown in Figure 1.

Where TD arranges transition process and generates the process's differential signal. Doing so, initial error of the system can be reduced. ESO gives the estimate value of the object status variable and system's disturbances.

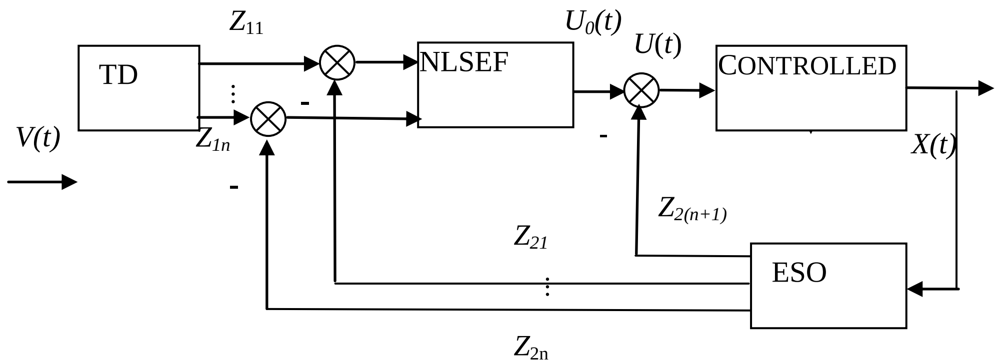

Figure 1. The Structure of ADRC Controller

The controller can transform nonlinear system which is disturbed by uncertain into an integral series structure of linear system by using nonlinear transformation. After that, we can design state error feedback controller. It isn't limited in linear form, can be more suitable non-linear configuration. Thus it give rise to a NLSEF. NLSEF need to be given control signal. Corresponding order ADRC controller equation can be written as:

$$\begin{cases} \dot{z}_{11} = -R_1 fal(z_{11} - v(t), \alpha_0, \delta_0) \\ \varepsilon = z_{11} - y \\ \dot{z}_{21} = z_{22} - \beta_1 fal(\varepsilon, \alpha_1, \delta_1) + b_0 u \\ \dot{z}_{22} = -\beta_2 fal(\varepsilon, \alpha_1, \delta_1) \\ \varepsilon_1 = z_{11} - z_{21} \\ u_0 = \beta_3 fal(\varepsilon_1, \alpha_2, \delta_2) \\ u = u_0 - z_{22} / b_0 \end{cases} \tag{3}$$

Where α, β, δ, R are parameters of the controller. Multi-order controller equation can be deduced by analogy.

The controller eliminates static error by compensating. ESO can estimate the unknown external disturbance and system's real-time value to compensate. ESO and NLSEF are not depending on the specific mathematical expression describe the object and the specific form of the external disturbance. Thus, appropriately selection on the nonlinear function and its parameters can make NLSEF become a good controller which has good adaptability and robustness in certain range of the object [14- 16]. So, $z_{21} \cdots z_{2n}$ in formula (3) can track system's n states $x, \dot{x}, \cdots, x^{(n-1)}$, z_{2n+1} track the disturbance. Paper [17] has given a select principle about non-linear function, here takes the form:

$$fal(\varepsilon, \alpha, \eta) = \begin{cases} |\varepsilon|^{\alpha} sign(\varepsilon), |\varepsilon| > \eta \\ \varepsilon / \eta^{1-\alpha}, |\varepsilon| \le \eta \end{cases} \quad \alpha > 0, \eta > 0 \tag{4}$$

2.2. Simulation of Auto-disturbance-rejection Controller

The following analysis based on the controlled system's transfer function is

$$G(s) = \frac{2}{s^2 + 6s + 1} \tag{5}$$

It's named system 1. It's a 2 orders linear controller, TD use a 2 orders linear form:

$$\begin{cases} \dot{z}_{11} = z_{12} \\ \dot{z}_{12} = r_1(v(t) - z_{11}) - r_2\dot{z}_{11} \end{cases} \tag{6}$$

State error feedback:

$$\begin{cases} u = k_1(z_{11} - z_{12}) + k_2(z_{11} - z_{12}) \\ u_0 = u - z_{22}/b \end{cases} \tag{7}$$

ESO use a 3 orders linear structure, its state equation is:

$$\begin{cases} e = z_{21} - x(t) \\ \dot{z}_{21} = z_{22} - \beta_1(e) \\ \dot{z}_{22} = z_{23} - \beta_2(e) + bu \\ \dot{z}_{23} = -\beta_3(e) \end{cases} \tag{8}$$

Where $x(t)$ is controlled system's output, u is controlled input, so z_{21}, z_{22} is the state estimation, z_{23} is the estimation of disturbance.

We have set up the PID and ADRC control systems to compare, the next three situations were simulated: controlled object was not be disturbed, plus disturbance and change the controlled object Parameters. Figure2 and figure3 are simulation results of the first situation.

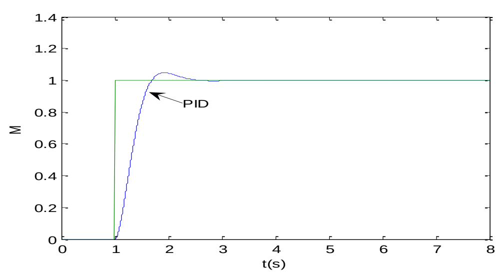

Figure 2. PID Response Curve

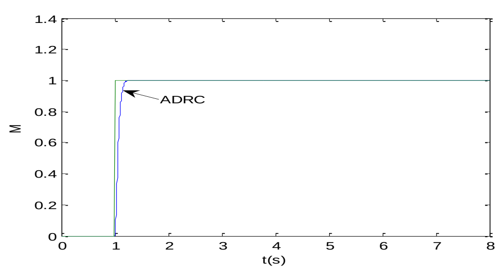

Figure 3. ADRC Response Curve

Figure 4 and Figure 5 are system 1's response curves when it is disturbed by different $w(t)$.

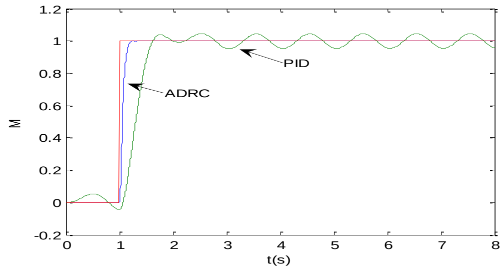

Figure 4. $w(t) = \sin t$

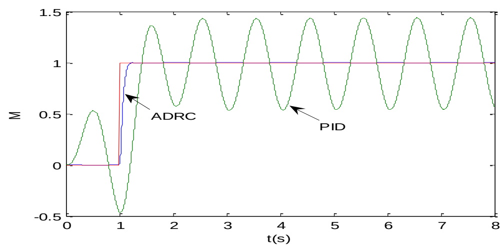

Figure 5. $w(t) = 10\sin t$

Figure 6 and Figure 7 are the response curves when change the controlled objects Parameters.

Simulate results show that ADRC and PID are robust too. But when the perturbation frequency is lower or its frequency is high and amplitude is large, ADRC has stronger immunity than PID. When perturbation frequency is high but amplitude is small, they have same immunity; PID control system has larger overshoot. If we make controller parameters unchanged, changes object's parameters only, adaptability and robustness of the ADRC should be better than the PID. Therefore ADRC has a better immunity characteristics and robustness for the object parameter changes than PID.

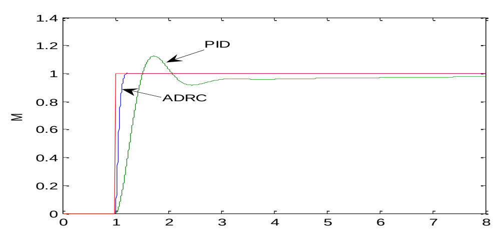

Figure 6. $G(s) = \dfrac{2}{s^2 + 4s + 2}$

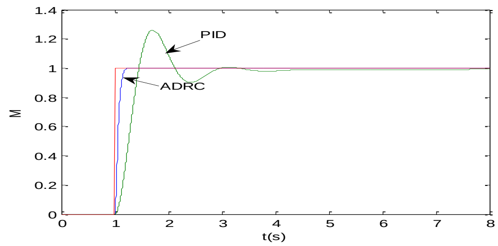

Figure 7. $G(s) = \dfrac{2}{s^2 + 3s + 1}$

3. Motor Control System based on ADRC

3.1. Model of Motor Control Sstem based on ADRC

Nowadays, research about application of ADRC technology in many aspects is being carried out. Brushless DC motor has advantages of simple structure, reliable operation and easy maintenance. With the rapid development of modern power electronics and computer technology, it has an increasingly wide range of applications in the industrial field. At the same time, its shortcomings such as large torque ripple and poor disturbance-rejection were paid close attention by more and more people. Traditional control methods can't meet the requirement of high precision, which need small torque ripple and high disturbance-rejection. In view of above, we have built a BLDCM control system based on ADRC.

According to BLDCM's model, it was equivalence to an integral series type object constituted by two nonlinear systems. We have devised two ADRC to achieve inner and outer ring control. The series structure's subsystems are current and speed subsystem. By the motor state equations:

$$\begin{cases} u_A = R i_A + (L - M)\dot{i}_A + e_A \\ u_B = R i_B + (L - M)\dot{i}_B + e_B \\ u_C = R i_C + (L - M)\dot{i}_C + e_C \end{cases} \tag{9}$$

Where u_A, u_B, u_C are phase voltage for the A, B, C, i_A, i_B, i_C are phase current, R is the armature winding resistance for each phase, L is winding self-inductance, M is winding mutual-inductance, e_A, e_B, e_C are counter-electromotive force. The next can be drawn:

$$\begin{cases} \dot{i}_A = -\dfrac{R i_A}{L - M} + \dfrac{u_A}{L - M} - \dfrac{e_A}{L - M} \\ \dot{i}_B = -\dfrac{R i_B}{L - M} + \dfrac{u_B}{L - M} - \dfrac{e_B}{L - M} \\ \dot{i}_C = -\dfrac{R i_C}{L - M} + \dfrac{u_C}{L - M} - \dfrac{e_C}{L - M} \end{cases} \tag{10}$$

By the motor mechanical equation:

$$T_{em} - T_L - D\omega = J\dot{\omega} \tag{11}$$

Where T_L is load torque, D is damping coefficient, ω is mechanical speed, J is rotational inertia. So,

$$\dot{\omega} = -\frac{D\omega}{J} + \frac{k_e i}{Jp} + -\frac{T_l}{J} \tag{12}$$

We defined:

$$\begin{cases} w_1(t) = -\dfrac{e}{L-M} \\ w_2(t) = -\dfrac{T_l}{J} \end{cases} \tag{13}$$

Series object equation can be drawn:

$$\begin{cases} \dot{i} = -\dfrac{Ri}{L-M} + \dfrac{u_s}{L-M} + w_1(t) \\ \dot{\omega} = -\dfrac{D\omega}{J} + \dfrac{k_e i}{Jp} + w_2(t) \end{cases} \tag{14}$$

Where i is armature current, e is counter-electromotive force of the armature windings of the two phase, u_s is voltage applied to the conduction windings, p is pole pair number of motor. k_e is electromotive force coefficient.

Current subsystem and speed subsystem use 1 order ADRC controller. The form of NLSEF is

$$u_0(t) = \sum_{i=1}^{n} \beta_i fal(\varepsilon_i, \alpha, \eta) \tag{15}$$

According to control equations of ADRC, control parameter of the ultimate controller is

$$u(t) = u_0(t) - z_2(t)/b \tag{16}$$

Where $z_2(t)$ is the disturbance estimation, b is the control input parameter.

Current subsystem makes the voltage of inverter's DC side as a control input, the current as a measurement input. Speed subsystem make i as control input, the electrical angular velocity ω is the measurement input. BLDCM's ADRC control scheme is shown in Figure 8.

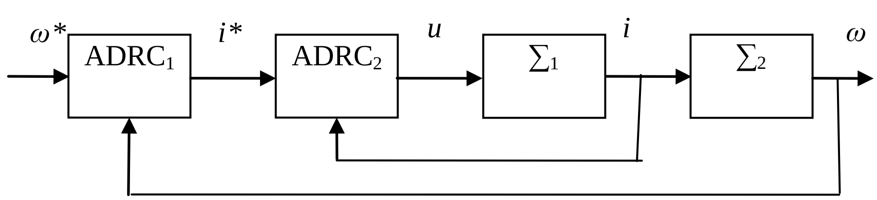

Figure 8. ADRC Diagram of BLDCM System

where ADRC2 and Σ1 composites current subsystem. ADRC1 and Σ2 composites speed subsystem. Given and feedback signal of speed is send into speed regulator (ADRC1) after compared. Output *i** of speed regulator is compared with current feedback and be send into current regulator (ADRC2) to give duty cycle signal u. By doing so, stator winding current can be controlled, and the inverter output current will follow a given current changes.

4. Experimental Results

We have build PID and ADRC system in matlab to verify the effects. Simulate prototype's parameters is $P = 400W$, $R = 7.82\Omega$, $T_e = 1.3Nm$, $n = 2500 r \cdot \min^{-1}$, $T_e = 1.3Nm$, $C_e = 0.76V \cdot (rad \cdot s)^{-1}$, $L - M = 40mH$, $U_N = 300V$, $J = 1.23 \times 10^{-4} kgm^2$ .Parameter's adjustment of ADRC starts from outer ring. Firstly, set inner ring's transfer function to 1. After determining parameters of outer ring, adding inner ring and adjust its parameters. In order to verify the system's static and dynamic performance, we given a sudden increase in load $T_e = 0.7 Nm$ to system when t=0.3 s after it running stable. Figure 9 to Figure 14 are their response curve.

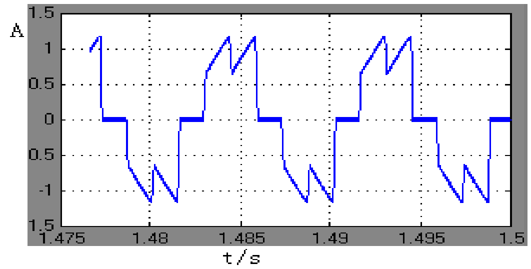

Figure 9. Phase Current (PID)

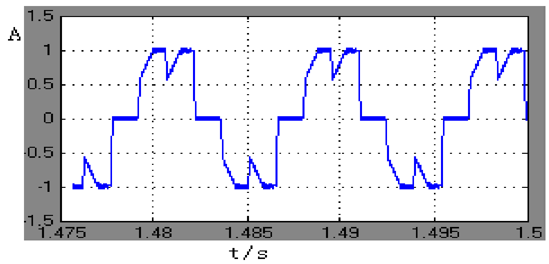

Figure 10. Phase Current (ADRC)

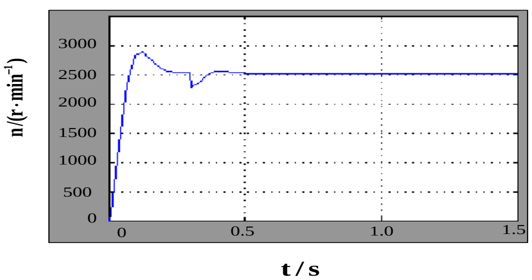

Figure 11. Speed Response (PID)

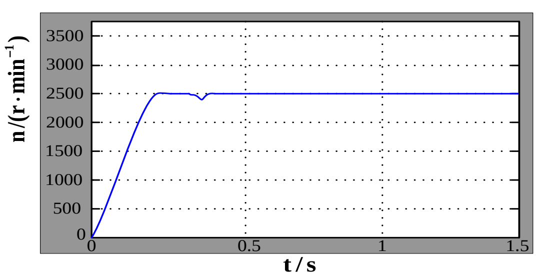

Figure 12. Speed Response (ADRC)

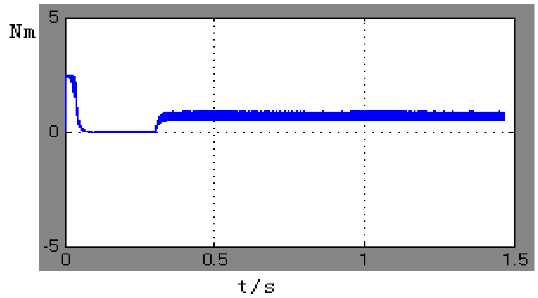

Figure 13.Torque Response (PID)

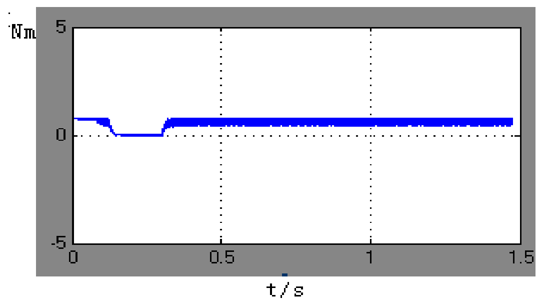

Figure 14. Torque Response (ADRC)

According to simulation results, it is obvious that ADRC control system has faster response. Its speed fluctuation is also stable relatively and current of each phase transited smoothly. ADRC controller has a good adaptive ability and which is superior to the traditional PID control system. The system can compensate disturbance dynamically when it is subjected by external disturbances.

5. Conclusions

Principle and characteristics of ADRC controller is analyzed theoretically in this paper. Its superiority relative to PID control method is analyzed theoretically too. Based on these analyses, simulations about PID controller and ADRC controller have been done. Simulation results fully verify the theoretical analysis results. We have introduced ADRC to BLDCM system to overcome its shortcomings. Simulation results show that ADRC controller has strong adaptability and robustness for the uncertainty of the model and the variation of external disturbance. At the same time, the system has a good dynamic response performance. Its anti-jamming performance and motor torque ripple suppression effects are superior to the traditional PID control system.

6. Future Work

The described method will be implemented on actual system.

The described method should be applied to other motor control system to get good results.

For real time control system, parameter adjustment method of ADRC needs to be improved to find the best value in the shortest possible time.

Acknowledgements

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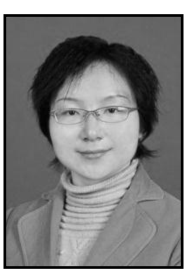
Authors



QiaoLing Yang received her M.S. degree in Power Electronics and Power Transmission from Lanzhou University of Technology. Now she is Dr under graduate of the Lanzhou University of Technology. At the same time, she is a teacher of Lanzhou University of Technology, and engaged in the field of control and power electronics and power transmission in teaching and scientific research work 12 years.

GuangQing Bao received her M.S. degree in Power Electronics and Power Transmission from Lanzhou University of Technology in 2003. She received her D. degrees in Electronics Engineering. Now she is a professor in Lanzhou University of Technology, doctoral tutor.

HaiPing Zhang received his bachelor's degree in Automatic from Northeast Electric Power University. Now he is a senior engineer in TianHua Research Institute of Chemical Machinery and Automation.