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Based on Anti-windup PI Brushless DC Motor Control System Design

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Abstract

In this paper, on the simulation model of brushless DC motor, for brushless DC motor speed controller adopts Anti-windup PI saturated controller. According to the output of the controller is saturated, integral output feedback to the input, by the integral state control. It is that integral controller using the conditions with the computing strategy of control algorithm, so ensure the controller when a saturated. As soon as possible from the saturated zone, reached the overshoot volume is reduced. The simulation experimental results show that the control method can effectively inhibit integral saturation and implement system response speed. It is good that the system has good robustness and steady-state performance.

Keyword: *brushless dc motor, anti-windup PI control, condition of integral, calculation method; saturated nonlinear*

1. Introduction

With the rapid development of electronic technology, the new motor control theory. Brushless dc motor with its simple structure, high reliability, good performance characteristics, has been widely used [1, 2]. As the application fields of BLDC motor continues to expand. The motor control system design requirements more and more high. Not only control system design should not only control algorithm is reasonable and effective, motor control performance is good, but also low cost, short development cycle. As a result, the motor simulation model on the basis of the study of its controller design is of great significance [3, 4].

In the paper, the simulation model of brushless dc motor controller algorithm is applied in Anti-windup PI control. Because the motor is non-linear, time-varying and system in the presence of static error, adjust proportion and integral coefficient. The traditional PID control algorithm is difficult to meet control requirements [5-7]. Anti-windup of the control algorithm is applied in this article is Conditional integral method and reverse Calculation method, with the combination of control strategy. Whether conditional integral method based on the output of the controller by limiting to choose integral action, make the controller in the P control and PI control to switch between nonlinear control method; reverse calculation method is the input and output of saturated nonlinear differential feedback to the integrator input terminal, reduce the integrator input, thus inhibiting the Windup phenomenon [8-10]. In this paper, the control algorithm guaranteed the controller appears when saturated. The exit of saturated as soon as possible, so that the overshoot volume is reduced. The simulation and experimental results indicate that design of the system parameters satisfy the performance requirements of the system. Not only make the system response speed, and make the control system achieved good control effect.

2. The Mathematical Model of Brushless DC Motor

Based on the three-phase six states, star connection brushless dc motor as an example to research design. It is based on the analysis of the mathematical model of brushless dc motor and electromagnetic torque and so on characteristics. The motor three-phase winding state equation:

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$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} r & 0 & 0 \\ 0 & r & 0 \\ 0 & 0 & r \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} di_a/dt \\ di_b/dt \\ di_c/dt \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

In the equation: u_a, u_b, u_c: a,b,c each phase winding voltage(V); i_a, i_b, i_c: a,b,c each phase winding current(A); $L-M$: effective electromagnetic induction(H); e_a, e_b, e_c: a,b,c contrary to the electromotive force(V); Motor electromagnetic torque generated by the stator current and rotor magnetic field. The electromagnetic torque expression is:

$$T_e = (ei_a + ei_b + ei_c) / w = K_T i \tag{2}$$

T_e: Electromagnetic torque ($N \cdot m$); w: mechanical angular velocity($rad \cdot s^{-1}$); K_T: coefficient of motor torque.
The equation of motion of the machine:

$$T_e - T_L = J\frac{dw}{dt} + B_v w \tag{3}$$

T_L: load torque($N \cdot m$); J: torque moment of inertia($kg \cdot m^2$); B_v: damping coefficient ($N \cdot m \cdot s \cdot rad^{-1}$).

3. Brushless DC Motor Control System Design

Anti-windup PI controller is made up of conditional integral method and calculation method of control strategy. It is purpose to make the system of saturated nonlinear output similar to saturated linear output without as much as possible. For PI controller, because of the controller has integral link, to windup phenomenon. The condition of integral method is a simple effective method to limit the phenomenon, thus stop or limit integral action.

3.1. Anti-windup PI Controller Design

According to the type (2) (3) the equation of motion of the machine, motor speed control system can be represented by the following first-order linear system:

$$\frac{dw_r}{dt} = \frac{1}{J}(K_T i(t) - T_L) - \frac{B}{J} w_r \tag{4}$$

Make $u_s = K_T i(t)$ for the controlled object of input, namely the reference current. Make the controlled object is u_s, saturated nonlinear effects as follows:

$$u_s = \begin{cases} i_{\max} \operatorname{sgn}(u_n), if \quad |u_n| > i_{\max} \\ u_n, \quad if \quad -i_{\max} \le u_n \le i_{\max} \end{cases} \tag{5}$$

$i_{\max}$: Maximum current input; $\operatorname{sgn}()$: symbolic function; u_n: output of the PI controller. The output function satisfies the conditions $-i_{\max} \le u_s \le i_{\max}$ for the linear area, or as the saturated zone.
The input and output are equal, namely linear area:

$$\dot{e}(t) + K_P e(t) = 0 \tag{6}$$

K_P : Proportional gain; $e = w_r^* - w_r$: speed error; w_r^* : given speed. So:

$$u_n = u_s = K_P e + \eta \quad (7)$$

η : integral state (the integrator output).

If a given rotational speed is a big step or a sudden load torque, and the PI controller output into the saturated zone, the output of the motor and the input range that cause Windup phenomenon. By using the calculation method, that is the difference between the output and input both constitute a feedback path ($u_n - u_s$) as feedback signal to eliminate the error due to saturation limit. It is purpose to suppressing Windup. Integral control law:

$$\dot{\eta} = k_i e - k_c (u_n - u_s) \quad (8)$$

k_i : integral gain; k_c : compensation coefficient.

Anti-windup of the PI controller, this paper according to the control output is saturated, the integral state control. One logical switch S to switch between 1 and 2, corresponds to the controller of the unsaturated zone and saturated zone. When connect with 1 S, the controller output for the saturated zone. As this time, feedback to the input end of the integrator. When S and 2, the controller output as the unsaturated zone, integrator accumulative speed error. The integral state η to meet:

$$\dot{\eta} = \begin{cases} k_i e - k_c (u_n - u_s), & if\ u_n \neq u_s \\ k_i e & , if\ u_n = u_s \end{cases} \quad (9)$$

3.2. The Stability of the System

When the controller into the saturated zone, motor input preference current limiting value that integral state rapidly converge to zero, and system in the saturated zone will automatically enter the linear region. When the output of the controller in the unsaturated zone (linear) that system is asymptotically stable. It is that prove the stability of the system and respectively in the saturated zone and linear stability analysis.

(1) The controller in the saturated zone, by type (4) available motor speed error equation is:

$$\dot{e} = -\frac{B}{J} e - \frac{1}{J}(K_T i - T_L) + \frac{B}{J} w_r^* \quad (10)$$

By type (8), integral saturation area:

$$\dot{\eta} = k_i e - k_c (u_n - u_c) \quad (11)$$

As integral state faster than speed error that it is immediately converge to zero when the integral state in the controller into the saturated zone. By type (7):

$$u_n = K_P e \quad (12)$$

When meet the $|e| \le i_{\max} / K_P = E_m$ conditions, the controller into the linear area, or in the saturated zone.

Define *Lyapunov* function:

$$V_1(e) = \frac{1}{2} e^2 \quad (13)$$

And:

$$\dot{V}_1(e) = e\dot{e} = -\frac{B}{J}e^2 - \frac{K_T e}{J}i + (\frac{T_L}{J} + \frac{B}{J}w_r^*)e \tag{14}$$

(5) and (12) into (14), to:

$$\dot{V}_1(e) = -\frac{B}{J}e^2 - \frac{K_T i_{\max}\,\mathrm{sgn}(K_P e)}{J}e + (\frac{T_L}{J} + \frac{B}{J}w_r^*)e \le -\frac{B}{J}e^2 + [-\frac{1}{J}(K_T i_{\max} - T_L) + \frac{B}{J}w_r^*]|e| \tag{15}$$

Make $\dot{V}_1(e) \le 0$, to:

$$|e| \ge -\frac{(K_T i_{\max} - T_L)}{B} + w_r^* \tag{16}$$

When meet the $|e| \le i_{\max} / K_P = E_m$ conditions enter the linear region, therefore return from saturated zone linear zone conditions as follows:

$$|T_L| + B|w_r^*| \le (\frac{B}{K_P} + K_T)i_{\max} \tag{17}$$

When the motor satisfy condition (17), Speed error $|e|$ will be smaller than E_m, and the controller at this time to return to the linear area.

(2) Controller in the linear area ($u_n = u_s$), integrator accumulation speed error, error equation:

$$\dot{e} = -(\frac{B}{J} + \frac{K_P}{J})e - \frac{1}{J}(\eta - T_L) + \frac{B}{J}w_r^* \tag{18}$$

Define $Lyapunov$ function:

$$V_2(e,\eta) = \frac{1}{2}Je^2 + \frac{1}{2K_i}(\eta - \eta_s)^2 \tag{19}$$

η_s: η's steady state value. Derivative with respect to:

$$\dot{V}_2(e,\eta) = -(B + K_P / J)e^2 + e[(Bw_r^* + T_L) - \eta_s] \tag{20}$$

Make $\dot{V}_2(e,\eta) \le 0$ and the integral state in the steady state $\eta_s = Bw_r^* + T_L$, so to get the linear stability condition:

$$|T_L| + B|w_r^*| \le K_T i_{\max} \tag{21}$$

When motor satisfy condition (21), the controller in the linear region in a gradual steady state.

3.3. Anti-windup PI Controller Simulation Model

According to the Anti-windup of the brushless dc motor principle of saturated nonlinear PI controller of MATLAB/SIMULINK modules are shown in Figure 1 below:

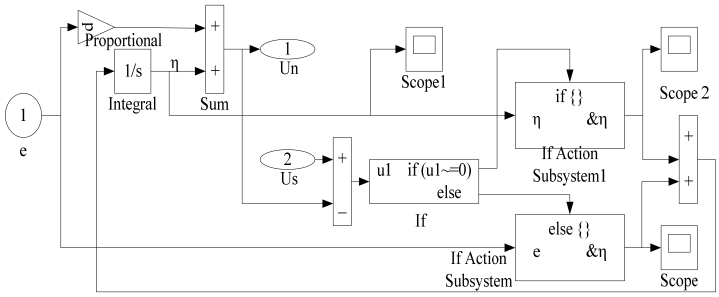

Figure 1. Anti-windup PI Controller Model

In this paper, based on the Anti-windup PI controller of the system is in response to a given step of the process. When $e(t)$ is smaller, the integrator backward integration in a timely manner, and make the integrator saturation back ahead of time, reduce the overshoot of the system. So Anti-windup PI controller can make the system response rapidity and no overshoot and make the system has good stability.

4. Simulation and Experimental Analysis

The system simulation is based on MATLAB/SIMULINK simulation model and to verify the effectiveness of Anti-windup PI controller. The simulation uses the motor parameters: rated voltage 220V, phase inductance: $L-M=0.0139H$, damping coefficient: $B=0.0002N*m*s/rad$, the moment of inertia: $J=0.05kg\cdot m^2$, winding resistance: $R=1\Omega$, a log: $np=1$, rated speed: $n=1200r/\min$. Anti-windup of PI controller parameters: $k_P=10$, $k_i=0.1$, compensation coefficient: $k_c=1$. The dynamic performance of the machine: no-load starting motor control system, after reaching the steady state. When $t=0.2s$ sudden load $T_L=1N\cdot m$, can get the speed of the system, current and counter electromotive force simulation curve as shown in figure:

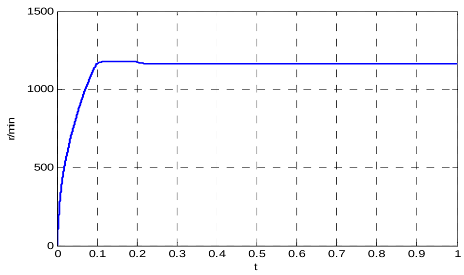

Figure 2. Speed Response Curve

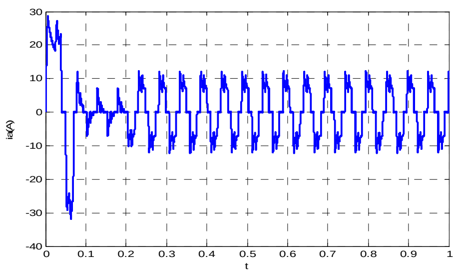

Figure 3. A Phase Current Response Curve

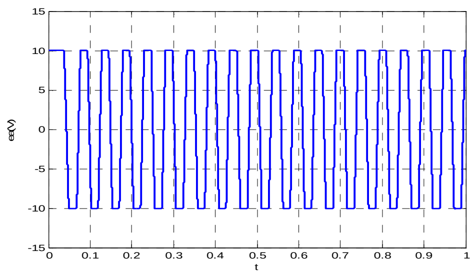

Figure 4. A Reverse Electromotive Force Response Curve

Experiment system analysis using TMS320F2812 digital signal processor as the controller, power drive circuit adopts the single bridge rectifier, IGBT inverter and a large capacitor filter. There is the current voltage hall sensor signal and the photoelectric encoder to detect motor speed. Not only with RS-232 serial communication port, but also the experimental data transmitted to the PC. The parameters of the motor and simulation is the same, and get the measured speed of the motor, current and counter electromotive force response curve:

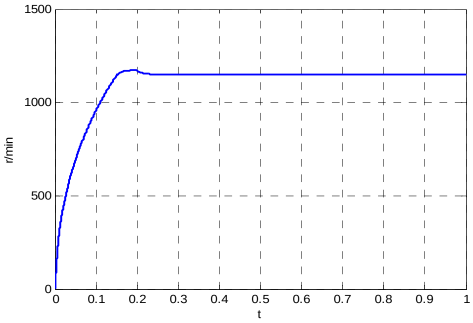

Figure 5. Speed Response Curve

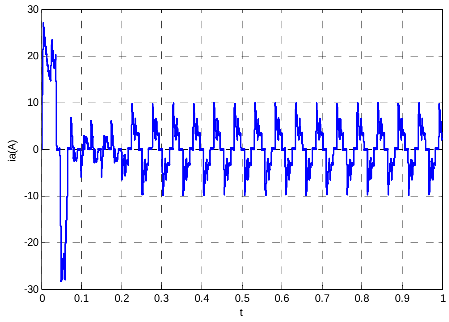

Figure 6. A Phase Current Response Curve

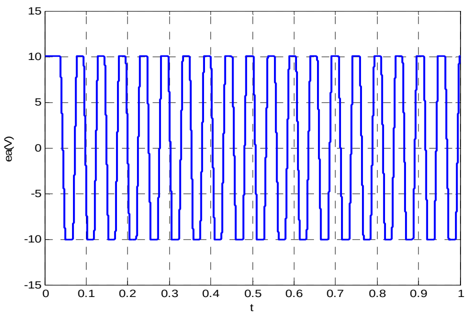

Figure 7. A Reverse Electromotive Force Response Curve

By simulation and experiment result: based on the Anti-windup PI controller design of brushless dc motor control system can effectively inhibit the windup phenomenon of the controller. Not only reduce the overshoot of system capacity and make the system response speed is fast, but also make the system in the case of load parameters has good dynamic and static performance.

5. Conclusion

In this paper, the Anti-windup PI controller is made up of condition of integral method and the calculation method of control strategy. The controller in the brushless dc motor control system has effectively suppressed the windup phenomenon of the controller. It is not only reduce the overshoot of the system and make the system response speed, floating adjustment, but also make the brushless dc motor control system has good robustness and dynamic and static performance.

References

[1] Shen Yan-xia, Chen Zhong-wei. Induction motor vector control system based on anti-windup controller. Industrial Electronics and Applications (ICIEA). 6th IEEE Conference on. 2011: 2729-2732.

[2] Kumar S, Negi R. *A comparative study of PID turning methods using anti-windup controller. Power, Control and Embedded Systems (ICPCES).* 2nd International Conference on. 2012: 1-4.

[3] Hwi-Beom Shin, Jong-Gyu Park. Anti-windup PID Controller with Integral State Predictor for Variable-Speed Motor Drives*. Industrial Electronics, IEEE Transaction on*. 2012: 1509-1516.
[4] Kaneko K, Ohishi K. Anti-windup robust controller considering motor dynamics for speed servo system. Machatronics (ICM). *IEEE International Conference on.* 2013: 694-699.
[5] Xiao W, Wen H, Zeineldin HH. *Affine parameterization and anti-windup approaches for controlling DC-DC converters*. Proceeding of Industrial Electronics (ISIE). 2012: 2801-2805.
[6] Jing cong Ma, Zhang Yang. *The control theory of permanent magnet synchronous motor based on anti-windup control.* Proceeding of Intelligent Control and Automation (WCICA). 2012: 2801-2805.
[7] Klinlaor K, Chuladaycha N. *Improved speed control using Anti-Windup PI controller for Direct Torque Control based on permanent magnet synchronous motor*. Proceedings of Control, Automation and Systems (ICCAS). 2012: 779-783.
[8] Miya Jima T, Fujimoto H, Fujitsuna. *Control method for IPMSM based on PTC and PWM hold model in over modulation range-Study on robustness and comparison with Anti-windup control*. Proceedings of Energy Conversion Congress and Exposition. 2010: 2844-2850.
[9] Hua LI, Jing Bai, Shujian Liao, Juanping Wu. Simulation Models for MIMO wireless channels. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2013; 11(1): 158-166.
[10] Zicheng Li, Zhouping Yin, Youlun Xiong, Xinzhi Liu. Rotor Speed and Stator Resistance Identification Scheme for Sensorless Induction Motor Drives. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2013; 11(1): 503-512.