Analysis of Various Anti-Windup Schemes used to Control PMDC Motors employed in Orthopedic Surgical Simulators

G. Murugananth[1], S. Vijayan [2], S. Muthukrishnan[3]

[1] Department of EEE, Pollachi Institute of Engineering and Technology, Pollachi, India.
E-mail: gmurugananth@gmail.com
[2] Principal, Surya Engineering College, Erode, India
[3] Department of ECE, Sri Eshwar College of Engineering, Coimbatore, India

Abstract: Orthopedic surgical simulators are used by the trainee surgeons to drill the bones and place the screws. These simulators use PMDC motors for bone drilling. In this paper a closed loop chopper controlled drive is proposed and evaluated. The chopper controlled drive has an inner current control loop and an outer speed control loop. The outer control loop employs a conventional PI controller for the speed control of the PMDC motor. The anti-windup PI controller based system is proposed in order to enhance the performance of the system. The system is simulated using Matlab / Simulink and the performances of various anti-windup schemes are analysed. The properties of these controllers were measured and tabulated. The simulation results inferred that the proposed closed loop system with tracking anti-windup schemes can be used for the effective control of the PMDC motor in orthopedic surgeries.

[G. Murugananth, S. Vijayan, S. Muthukrishnan. **Analysis of Various Anti-Windup Schemes used to Control PMDC Motors employed in Orthopedic Surgical Simulators** *Life Sci J* 2013;10(1):226-230] (ISSN:1097-8135). http://www.lifesciencesite.com. 35

Keywords: Anti-windup, chopper, maximum peak overshoot, orthopedic surgical simulator, PI controller, PMDC Motor

1. Introduction

Novice surgeons practice drilling and screw placements in cadaver bones rather than live patients. The use of orthopedic surgical simulators for practicing drilling and screwing can help for such practices (Ann Majewicz et al, Chantelle et al, R. Thomas et al). The drilling and screwing of bones depends on the resistive force offered by the bones and the screw geometry respectively (R. Thomas et al, Ming-Dar Tsai et al, Olga Sourina et al and Robert V. O et al) . The resistive force offered by the un-fractured bones will be more while that of the fractured will be less. The screwing of the bones is done in three phases namely insertion, tightening and stripping (Ann Majewicz et al, Chantelle and Robert V. O et al). Different torque and speed combinations are needed for optimal placement of screws.

In the surgical simulators PMDC motors are used, because of their linear speed torque characteristics. The mathematical model of the motor is derived (R. Sankar, S. Ramareddy & N. Chandrasekar, K. Thiyagarajah). The speed control of the motor is employed with conventional PI controller for various applications which include rock drilling and robotics (Robert V. O et al, R. Sankar, S. Ramareddy & N. Chandrasekar, K. Thiyagarajah, Michel E Fisher et al and Nitai Pal et al). In this paper a closed loop chopper controlled system with an inner current control loop and an outer speed control loop is attempted. The inner current control loop uses a hysteresis controller. The outer speed loop is employed with a PI controller and is simulated using Matlab/Simulink. The various parameters are measured and tabulated.

The anti-windup phenomenon improves the transient state performance. The various types of anti-windup mechanisms are studied (R. Hanus et al, Youbin Peng et al, G. Murugananth et al). These anti-windup mechanisms are simulated using Matlab/Simulink and their transient state performances were analysed and compared with conventional PI controller based system.

2. Mathematical Model of PMDC Motor

The advantages of PMDC motor include linear speed – torque characteristics with high stalling torque and reduced power loss. Due to these advantages the PMDC motors are widely used in orthopedic surgical simulators. The mathematical model of the motor is derived from the following equations.

$$V = E + IaRa + La\frac{dIa}{dt} \quad (1)$$

$$E = K_1\omega \quad (2)$$

$$T_E = T_L + B\omega + J\frac{d\omega}{dt} \quad (3)$$

$$T_E = K_2 Ia \quad (4)$$

Where,

R_a = Armature Resistance in Ohms
L_a = Armature Inductance in H
I_a = Armature Current in A
E = Back EMF in Volts
K_1 = Voltage Constant in volts sec/rads
ω = Angular Speed in rads/sec
T_E = Electromagnetic torque developed
T_L = Load torque in Nm
J = Moment of Inertia in kg.m^2/s^2
B = Damping Coefficient in Nms
K_2 = Torque Constant in Nm/A

Figure 1 illustrates the mathematical model of the PMDC motor derived from the above equations.

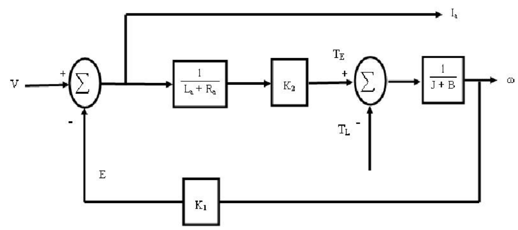

Figure1. Mathematical Model of PMDC Motor

3. Proposed System

The proposed closed loop control system consists of two power electronics switches S1 and S2. Switch S1 is used to regulate the speed of the motor in the outer speed control loop and S2 is used for On/Off control. An inner current control loop and an outer speed control loop as shown in Figure 2. The current control loop employs a hysteresis control system and the outer speed control loop employs a PI control system.

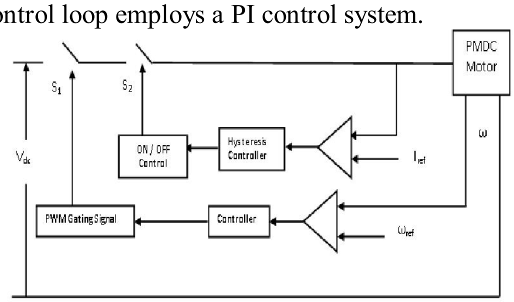

Figure 2 - Block Diagram of the Proposed System

3. 1. Inner Current Control Loop

The inner current control loop is meant for ON/OFF control of the switch S2. The torque required for drilling and the screw placements differs for fractured and un-fractured bones. The un-fractured bones have good strength and so the resistive force required by them increases. This in-turn increase the torque required to drill them. During surgery the un-fractured bones should not be drilled. In PMDC motors torque is a function of current. Here torque is measured in terms of current and compared with the set value. The difference between the set value and the present values drives the hysteresis controller and the controller controls switch S2. During drilling or screwing when the drill bit reaches or touches the un-fractured bone the torque required increases. This increase in torque is sensed and compared with the set value and the error is processed by the hysteresis controller. As the torque value is increased, the controller generates appropriate pulse to switch off the switch S2.

3.2. Outer Speed Control Loop

The three phases of screwing such as insertion, tightening and stripping needs three different levels of speed in the motor. Based on the operation the value of speed is set. The current speed of the motor is sensed and is compared with the set value. The error is processed by the PI controller, which in-turn generates the required PWM signal for the switch S1. The switch S1 generates the required voltage for the motor and thus the speed of the motor is controlled.

3.3. Conventional PI Controller

The schematic model of the PI controller is shown in Figure 3. The speed error is calculated from the current speed and set speed and is given to the controller. The controller processes the speed error and generates the required pwm signal for the chopper.

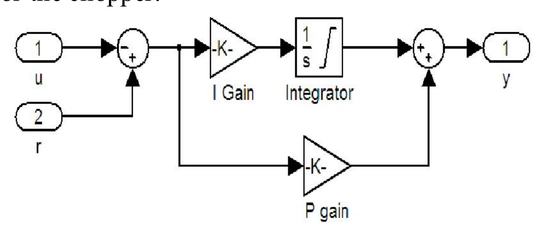

Figure 3 - Schematic Model of Conventional PI Controller

4. Anti-Windup PI Controller

PMDC Motors consists of a permanent magnet field system. When a linear control system is designed for the control of the these motors, employing an integral action and a limiter, then the integrator will integrate the error signal such that the integral term may become very large if integration lasts for a long time and saturation occurs. This is termed as windup problem.

The windup phenomenon can be avoided by keeping the integrator output value within limits is called Anti-Windup control. The anti-windup schemes are used to limit the over value in the integrator and reduces the integration time and hence, the overshoot and steady state error.

In PMDC motors, the relationship between speed and voltage is linear. To improve the dynamic state of the PMDC motor the Anti-Wind up PI controller is employed. The schematic model of the anti-windup PI controller is shown in Figure 4.

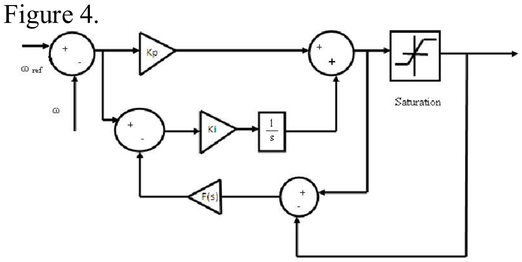

Figure 4 - Schematic Model of Anti-Windup PI Controller

There are various anti-windup PI schemes which include back calculation, conditioned, anti-windup with dead zone, anti-windup with tracking, anti-windup tracking with gain etc. In this paper we attempted with back calculation, anti-windup with dead zone and tracking schemes.

4.1. Back Calculation Anti-Windup Scheme

The model of back calculation anti-windup scheme is shown in Figure 5. In this scheme the integral limit is set form the feedback of the output signal. In back-calculation technique the integral term is calculated based on the saturation of the output. The schematic model of back calculation scheme is shown in Figure 5.

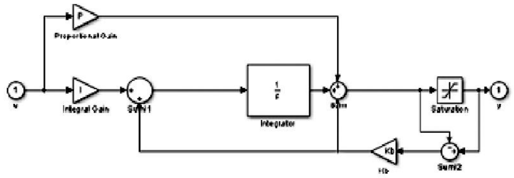

Figure 5 - Back Calculation Anti-Windup Scheme

4.2. Anti-Windup with Dead Zone

Anti-Windup with dead zone scheme utilizes a dead zone element to control the integral limit as shown in Fig. 6. The integral value remains linear and unchanged until it achieves the dead zone limit. Once it becomes higher than the dead zone limit, then the total integral value is reduced.

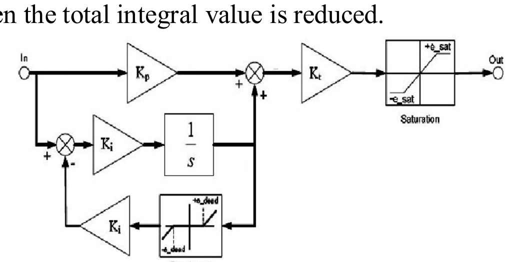

Figure 6 - Anti-Windup with Dead Zone

4. 3. Anti-Windup with Tracking

The tracking scheme calculates the difference between the input and output saturation block and reduces the integrator's value.

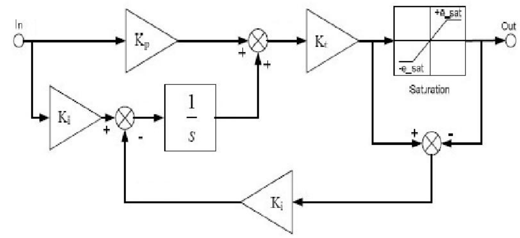

Figure 7 - Anti-Windup with Tracking

5. Simulation Results

The proposed closed loop chopper controlled system is simulated using Matlab/Simulink. The simulation model of the system is shown in Fig. 8. The torque error determined from the current and set torque values is processed by the hysteresis controller and inturn controls the ON/OFF condition of switch S2. The speed error is determined form the current speed and set speed values and is porcessed by the PI controller and it generates the approporiate PWM signal needed for siwtch S1. The Zeigler – Nichols method of tuning is used to fix the values of proportional and integral gains. The response of the system with PI controller is shown in Figure 9.

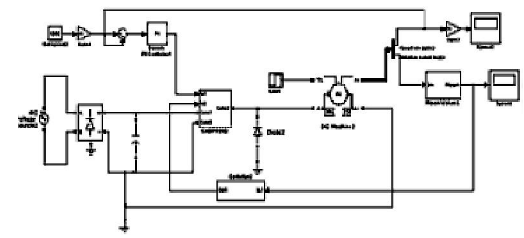

Figure 8 - Matlab / Simulink Model of the Proposed System

Table 1 – Motor Specifications

Output Power	52 W
Voltage	9V
Rated Speed	4990 rpm
Armature Resistance	1 ohms
Armature Inductance	0.13mH

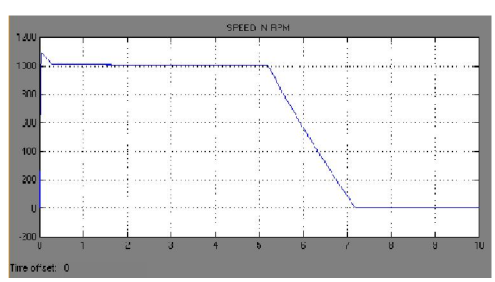

Figure 9 - Response of Conventional PI Controller

The comparative analysis of the conventional PI and the three schemes of anti-windup PI controller are shown in Figure 10. The results infer that there is a drastic change in the maximum peak overshoot compared to the conventional PI controller and the other anti-windup schemes.

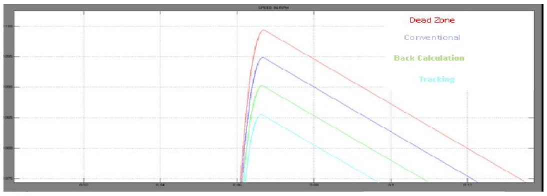

Figure 10 - Comparative Analysis of Conventional and Anti-Windup PI Controllers

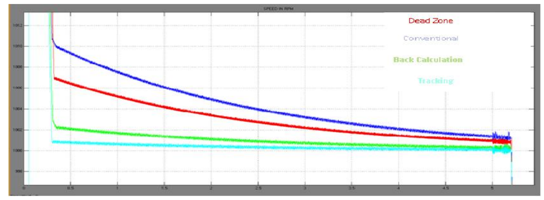

Figure 11 - Steady State Response of Conventional and Anti-Windup PI Controllers

The comparative result implies that in the anti-windup scheme with dead zone, the integral limit is not adjusted, which results in large peak overshoot. The gain of the tracking system is the cause for reduced peak overshoot in the tracking anti-windup scheme. The transient and steady state responses of the systems are tabulated from the simulation results as shown in Table 2 and Table 3 for various speed values.

Table – 2 – Simulated Parameters for Set Speed = 1000 RPM

Parameter	Conventional PI	Anti-Windup Scheme		
		Dead Zone	Back Calculation	Tracking
Maximum Peak Overshoot	9.5 %	9.9 %	9.1 %	8.5 %
Steady State Error	1%	0.65%	0.2%	0.1%
Rise Time (ms)	0.063	0.063	0.062	0.062
Settling Time (ms)	0.55	0.35	0.31	0.3

Table – 3 – Simulated parameters for Set Speed = 2500 RPM

Parameter	Conventional PI	Anti-Windup Scheme		
		Dead Zone	Back Calculation	Tracking
Maximum Peak Overshoot	10.2 %	10.6%	9.5 %	9.1 %
Steady State Error	1.6%	0.7%	0.4%	0.16%
Rise Time (ms)	0.07	0.07	0.07	0.068
Settling Time (ms)	0.6	0.45	0.4	0.4

6. Conclusions

A closed loop chopper controlled drive system is proposed for orthopedic surgical simulators. The simulation results of the proposed system shows that the speed becomes zero when there is a sudden increase in the torque value. The transient and steady state analyses show that by using the anti-windup techniques the performance of the system can be improved. Finally it is concluded that the system with tracking anti-windup scheme can give better performance by reducing the peak overshoot and with low rise and settling time. By the way this proposed system can be used in orthopedic surgical simulators.

Corresponding Author:
Prof. G. Murugananth
Department of EEE
Pollachi Institute of Engineering and Technology
Pollachi, Tamilnadu, India
E-mail: gmurugananth@gmail.com

References

1. Ann Majewicz, Jason Glasser, Rosemary Bauer, Stephen M. Belkoff, Simon C. Mears, Allison M. Okamur, “Design of a Haptic Simulator for Osteosynthesis Screw Insertion”, IEEE Haptics Symposium 2010, 25 - 26 March 2010, Waltham, Massachusetts, USA, pp 497-500.
2. Chantelle Saegenschnitter, Tania Walker, “Orthopedic surgical simulator”, S.M.B.E. (SA) Inc. Newsletter Vol. X1 No 1, 2003 pp1-2.
3. R. Thomas, et al., “Automated surgical screwdriver: Automated screw placement,” Proceedings of the Institution of Mechanical Engineers, vol. 222, no. 5, June 2008, pp. 451–454.
4. Ming-Dar Tsai, Ming-Shium Hsieh, Chiung-Hsin Tsai, “Bone drilling haptic interaction for

orthopedic surgical simulator", ELSEVIER - Computers in Biology and Medicine, volume 3,2007, 1 pp1709 – 1718.
5. Olga Sourina, Alexei Sourin, Howe Tet Sen,"Orthopedic Surgery Training Simulation", Journal of Mechanics in Medicine and Biology, Volume 7, No. 1 2007, pp 37–53.
6. Robert V. O' Toole, Branklajva Ramaz, Anthony M, DrrGlora III, Chrsitopher. D, Visnica and Robert H. Reid, "Biomechanics for Preoperative Planning and Surgical Simulations in Orthopedics", ELSEVIER - Computers in Biology and Medicine, volume 25, No. 2, 1995, pp183 – 191.
7. R. Sankar, S. Ramareddy, "A Novel Control Strategy Using Neuro-Fuzzy Controller for PMDC Drive", European Journal of Scientific Research, Volume 54 No.1, 2011, pp.29-45.
8. N. Chandrasekaran, K. Thiyagarajah, "Modeling and MATLAB Simulation of Pumping System using PMDC Motor Powered by Solar System", European Journal of Scientific Research, Volume 59 No.1, 2011, pp.6-13.
9. Michael E. Fisher Arindam Ghosh Adel M. Sharaf, "Intelligent Control Strategies for Permanent Magnet DC Motor Drives", Proceedings of the 1996 International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth, Volume No. 1, 8-11 Jan 1996, pp 360-366.
10. Nitai Pal, Pradip Kumar Sadhu and R. Swaroop, "Closed Loop Speed Control of DC Motors used in Rock Drilling and Mud Pump Application", Proceedings of the International Multi conference of Engineers and Computer Scientists, Volume 2, March 2012, pp 14-16.
11. R. Hanus, M. Kinnaert and J.L. Henrotte "Conditioning Technique, a General Anti-windup and Bumpless Transfer Method", Automatica, Vol. 23, No. 6, pp729-739, 1987
12. Youbin Peng, Damir Vrancic, and Raymond Hanus, "Anti-Windup, Bumpless, and Conditioned Transfer Techniques for PID Controllers", IEEE Control Systems Mag., 16(4), 48-57, 1996.
13. Hayk Markaroglu Mujde Guzelkaya Ibrahim Eksin Engin Yesil, "Tracking Time Adjustment in Back Calculation Anti-Windup Scheme", Proceedings 20th European Conference on Modelling and Simulation, Wolfgang Borutzky, Alessandra Orsoni, Richard Zobel, 2006.
14. J. Espina, A. Arias, J. Balcells, C. Ortega & S. Galceran, "Speed Anti-Windup PI strategies review for Field Oriented Control of Permanent Magnet Synchronous Machines Servo Drives with Matrix Converters".
15. G. Murugananth and S. Vijayan, "Performance Evaluation of PMDC Motors using Anti - Windup PI Controller", European Journal of Scientific Research, Volume 85 No.2 September 2012, pp 218-224.
16. G. Murugananth and S. Vijayan, S. John Alexis and S. Muthukrishnan, "A Comparative Analysis of PI, PID and Anti-Windup PI Schemes for PMDC Motors", International Journal of Computer Applications (0975 – 8887) Volume 57– No.2, November 2012, pp 21-25.

12/15/2012