CHAPTER 3

INTEGRAL WIND-UP AND ANTI-WINDUP TECHNIQUES

3.1 INTRODUCTION

The saturation in the system controller will cause the integral wind-up problem. This chapter focuses on the issue of wind-up phenomenon and the anti-windup techniques used to overcome them has been suggested. The various types of anti-windup schemes have been studied. The chopper controlled drive employed with the anti-windup schemes and the response of the drive system have been analyzed for the drilling and screwing modes of operation using MATLAB/Simulink.

3.2 BACKGROUND STUDY OF ANTI-WINDUP TECHNIQUES

Mostly control circuitry of variable speed drives are employed with PI controllers. The control schemes of these drives has two loops viz., inner current control loop and outer speed control loop. The inner current control loop provides a fast dynamic response and peak current protection. The outer speed control loop generates the command for current controller. In these controllers, the current command is limited to a maximum value, which causes the integral state to be inconsistent and becomes very large, causing the integral wind up phenomenon. Krikelis et al (1984) studied the effects of integral wind-up phenomenon and found that in variable speed drives, they cause large overshoot, a slow settling time and sometimes even instability in the speed response. The anti-windup schemes are used to overcome the effect of integral wind-up problem. There exist many anti-windup schemes, which
can be classified into three categories as conditional integration, the tracking back calculation and the limited integrator schemes. Hanus et al (1987); Astrom & Hagglund (2001); Jul-Ki Seok et al (2007); Walgama et al (1992); Jong-Woon Choi et al (2009) proposed the conditional integration anti-windup technique. In this method, the integral action is suspended and only the proportional action is activated, when the control input is saturated. Hwi-Beom Shin (1998); Jong-Gyu Park et al (2002); Ohishi (2006) suggested the tracking based anti-windup scheme for variable speed motor drives. This scheme utilizes the difference between saturated and the unsaturated control input signals to generate the feedback signal to act on the integrator input. In these schemes, the overshoot depends on the feedback gain of the control difference rather than the PI gains. Krikelis (1980), proposed the limited integrator scheme, in which the integrator value is limited by feeding the control back with a high-gain dead zone. This phenomenon ensures reliable operation in the linear region. Xin-lan Li et al (2011) compared and evaluated the aforesaid anti-windup techniques and proposed a novel method of anti-windup technique with integral state prediction. Hwi-Beom Shin & Jong-Gyu Park (2012) proposed a new anti-windup PID controller to improve the performance of variable speed drives and physically realized the same for the speed control of a vector-controlled induction motor drive fed by a pulse width modulated voltage source inverter.

In this Thesis, the integral wind-up problem and the anti-windup techniques to overcome it have been illustrated. The following anti-windup schemes employed in the chopper controlled drive of PMDC motor have been simulated and their responses have been analyzed to ascertain their performance.

1. Back calculation
2. Conditional integration
3. Anti-windup with dead zone
4. Anti-windup with tracking
3.3 INTEGRAL WIND-UP

The effect caused by real actuators having an input – output characteristic involving saturation or limiting the actuation output is termed as integral wind-up. In the PMDC motor drive system, the actuator control signal will produce a limited or saturated actuator output. Figure 3.1 shows the effect of the saturation characteristic.

![Diagram](image)

**Figure 3.1 Effect of Saturation Characteristic**

The integral wind-up phenomenon has been illustrated using the simulated results obtained from the MATLAB/Simulink model as shown in Figure 3.2 (a). To understand this phenomenon, the step signal has been given as input and it is set to +1 at t=0 and is switched to -1 at t=10 seconds. The simulated results of the input step signal, the output of the PI controller and the actuator are shown in Figure 3.2 (b). The integrator in the PI controller integrates the step input so that a peak of the response occurs at t=10 seconds and the integrator starts the long descent after the step has changed sign. This effect is wind-up of the integrator.
In the closed loop control system, if the control signal enters a saturation region and becomes constant, then the system reverts to open loop control. This makes the system to be more unstable. The application of this constant signal input causes an excessive overshoot in the process output. In this constant signal period, the action demanded by the controller cannot be delivered by actuator.
Figure 3.3 Comparisons of PI Controller and Actuator Outputs

In the Figure 3.3, at $t = 10$ seconds, the error $e(t)$ changes from positive to negative and the output of PI controller reaches its peak. The integrator now begins to unwind until $t = 18$ seconds. During this period, the control signal enters the linear region and the controller becomes more effective. Owing to these reasons, the winding and unwinding action of the integrator delays the effectiveness of the control signal. To avoid the wind-up effect, the integral term should be switched off as soon as the control signal enters the saturation region. Thus the anti-windup circuit is a scheme which determines the switching of the integrator. It may be noted that whenever the saturation occurs at the actuator’s output the integrator is turned OFF by the anti-windup circuit.

3.4 ANTI-WINDUP CIRCUIT

The integral wind-up phenomenon can be overcome by using anti-windup circuits. The anti-windup circuits detect when actuator saturation is reached and then switches off the integral action. When the control signal returns to the linear region, then the integral action will resume. A simple anti-windup circuit for PI controller has been simulated as shown in Figure 3.4.
Figure 3.4 Simple Anti-windup Circuit for PI Controller

In the above circuit, when switch $Sw = 0$, then the input to the integrator is zero and so the integral action will be stopped. For normal operation $Sw = 1$. If the output of PI control remains in linear unsaturated region, then the switch $Sw = 1$. When it enters the saturation region, then the switch $Sw = 0$. This disintegrates the integrator action and the integrator output is held at a constant value. The actuator output takes the saturation level at this time. This situation is maintained until the output falls back in the linear region. When this happens then the switch $Sw = 1$ and the integral action is resumed. The phenomenon of integral wind-up and the use of anti-windup circuit to overcome it are discussed in detail with an example in Appendix 1.

3.5 CHOPPER CONTROLLED DRIVE WITH ANTI-WINDUP TECHNIQUES

The wind-up phenomenon is due to the integral action. It is known that all the actuators have limitations on certain aspects. For instance, in the motor speed control system, the motor speed is limited. In the speed control systems with wide operating ranges, the control variables reach the actuator limits and break the feedback loop. Hence the system runs in open loop mode.
Thus the error is integrated continuously and this is termed as windup problem. When the actuator saturates, the consequence of this integral action will lead to large transients in the speed control system.

The field system of PMDC motor is made of permanent magnet. Hence the control of the motor depends only on the voltage supplied to the armature winding. In this motor the relationship between voltage and speed is linear. When a linear control system is designed for the control of these motors employing proportional and integral action, the integrator will integrate the error signal such that the integral term may become very large. If integration lasts for a long time the saturation occurs and peak overshoot increases. The closed loop chopper controlled drive for PMDC motor consists of conventional PI controller in the outer speed control loop as discussed in chapter 2, is replaced by various anti-windup techniques viz., as conditional integration, back calculation, dead zone and tracking.

3.5.1 Back Calculation Anti-windup Scheme

The model of back calculation anti-windup scheme is shown in Figure 3.5 (a). In this scheme the integral limit is set from the feedback of the output signal. In back-calculation technique the integral term is calculated based on the saturation of the output. The speed error is processed by the proportional gain and the integral gain. The anti-windup gain of the system is $K_a = 1/K_p$. $K_a$ is set to a large value in order to limit the integrator quickly. When the output of PI controller is saturated, the integral state is reduced with the rate of integral time constant by negativly feeding back the controller output. The integrator is reset dynamically with a time constant $T_i$. On the other hand, when the output is not saturated, the integral state accumulates a speed error and the PI action is activated.
The back calculation scheme has an additional feedback loop, which is formed by calculating the difference between the controller output and the actuator output. This error is fed back to the integrator through anti-windup gain $K_a$. When there is no saturation, the error is zero and will not have any effect on the normal operation. When saturation occurs in the actuator, the normal feedback path breaks as the process input remains constant. The additional feedback path remains unchanged and causes the integrator output to be driven to a value such that the integrator input becomes zero. Thus the back calculation scheme prevents the integrator from winding up.

3.5.2 Conditional Integration Anti-windup Scheme

Conditional integration anti-windup technique is similar to back calculation technique. In this method the integration is turned off when the control is far from steady state. Integral action is used when certain conditions are met, otherwise the integral term is held constant. If the controller output is saturated i.e., integration is shut off if error is positive; when error is negative, then the integrator input is set to a constant value. The schematic model of conditional integration anti-windup is shown in Figure 3.5 (b).

3.5.3 Anti-windup with Dead Zone

The anti-windup PI compensator with dead zone is shown in Figure 3.5 (c). The part of the integrated error is given to the dead zone and is used to control the integral limit. 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. The main drawback of this scheme is due to large integral limit, if the limit value is not adjusted properly, it makes the PI controller to produce either a large overshoot or undershoot.
3.5.4 Anti-windup with Tracking

The tracking scheme calculates the difference between the input and output saturation block and reduces the integrator’s value. The error is processed through the gain in order to reduce the peak overshoot. Increasing the value of gain will cause the peak overshoot to reduce. The schematic model of anti-windup with tracking is shown in Figure 3.5 (d).

(a) Back Calculation

(b) Conditional Integration Anti-windup

Figure 3.5 (Continued)
3.6 SIMULATION OF THE CHOPEER DRIVE WITH VARIOUS ANTI-WINDUP SCHEMES

The chopper controlled drive for the PMDC motor has been simulated with the aforesaid anti-windup techniques. The optimum value of proportional gain $K_p$ and integral gain $K_i$ are fixed as 7 and 3 respectively, as discussed in chapter 2. Using these gain values the PI controller is tuned with anti-windup schemes. The system has been simulated for the set speed of ranging from 300 to 2000 rpm and the response has been analyzed for the
proposed anti-windup techniques in the drilling and screwing modes. The response of back calculation anti-windup technique is shown in Figure 3.6 (a). The response of other techniques viz., conditional integration, dead zone and tracking anti-windup is shown in Figures 3.6 (b), 3.6(c) and 3.6(d) respectively.

(i) Drilling Mode

(ii) Screwing Mode

(a) Back Calculation Anti-windup Scheme

Figure 3.6 (Continued)
(i) Drilling Mode

(ii) Screwing Mode

(b) Conditional Integration Anti-windup Scheme

Figure 3.6 (Continued)
(i) Drilling Mode

(ii) Screwing Mode

(c) Dead Zone Anti-windup Scheme

Figure 3.6 (Continued)
(i) Drilling Mode

(ii) Screwing Mode

(d) Anti-windup Scheme with Tracking
3.7 RESULTS AND DISCUSSIONS

The parameters peak overshoot, steady state error and the motor idling (decelerating) time are measured from the simulated responses of the chopper drive with anti-windup techniques.
Figure 3.7 Performance Characteristics of various Anti-windup Schemes

3.7.1 Inference of Comparative Analysis

The figure 3.7 illustrates the performance of the anti-windup techniques. The peak overshoot of the dead zone anti-windup scheme is higher than the other anti-windup scheme the anti-windup scheme with tracking results in reduced peak overshoot compared to the other techniques. At low set speed of 300 rpm, the peak overshoot of dead zone anti-windup scheme was found to be 46%, which is the highest among all the anti-windup schemes. The anti-windup with tracking offers lowest peak overshoot of 39%. 
The conditional integration and back calculation schemes resulted in 44% and 42% respectively. For a medium speed of 1000 rpm, the dead zone scheme generates highest peak overshoot of 14%, whereas the anti-windup with tracking produced a lowest value of 7%. The schemes with conditional integration and back calculation exhibit peak overshoot of 11% and 8.5% respectively, which are higher than the tracking scheme. Though all AWPI scheme deliver very low peak overshoot at higher set speeds, the tracking AWPI scheme is lowest among them. For instance, at a speed of 2000 rpm, the peak overshoot of the tracking AWPI scheme is only 2.5%, whereas this value is higher in the case of other schemes. The peak overshoot of dead zone and conditional integration schemes is 6% and 3.5% respectively and it is 3% in the case of back calculation AWPI scheme.

A large difference in the steady state error of the schemes of interest has been observed from the simulation results. When the drive is made to run at a low speed of 300 rpm, the steady state error of conditional integration AWPI scheme is higher with 7.2% whereas the anti-windup with tracking scheme has only 2% of steady state error. The other schemes viz., back calculation and dead zone produce 2.9% and 6% respectively.

For the set speed of 1000 rpm, the conditional integration scheme provides 0.68% steady state error and anti-windup with tracking scheme gives lower steady state error of 0.26%. The steady state error of back calculation and dead zone are 0.42% and 0.55% respectively which are slightly higher than the tracking AWPI scheme. When the drive is set to run at a high speed of 2000 rpm, the steady state error occurred in the conditional integration, dead zone, back calculation and tracking schemes was 0.28%, 0.15%, 0.12% and 0.05% respectively. Therefore it has been construed that at high speeds the steady state error is very less and it is less than 1%.
The motor idling time varies with respect to set speed. For low set speed values, the idling time is less and it is more at higher speeds. For instance, when the set speed is 300 rpm, the idling time has been 0.52 seconds for dead zone scheme, 0.47 seconds for conditional integration AWPI scheme, 0.43 seconds for back calculation scheme and it is 0.4 seconds with tracking AWPI scheme. The same sort of results has been observed for medium and high speed ranges. For a set speed of 1000 rpm, the tracking scheme has 0.6 seconds of idling time which is less compared to the other schemes. The idling time for the dead zone, conditional integration and back calculation schemes are 0.78 seconds, 0.72 seconds and 0.62 seconds respectively. For high set speed of 2000 rpm, the corresponding idling period are 2.5 seconds, 2.3 seconds, 2.1 seconds and 1.85 seconds for dead zone, conditional integration, back calculation and tracking schemes.

From the simulation result, it is vibrant that the effect of saturation plays a vital role in the transient and steady state response of the chopper drive. The dead zone scheme provides highest peak overshoot compared to the other schemes and the conditional integration scheme results in more steady state error. The back calculation scheme provides reasonably less peak overshoot and steady state error when compared to dead zone and conditional integration schemes, and it is slightly higher than anti-windup with tracking scheme. Among all the schemes, there is a momentous reduction in both the peak overshoot and steady state errors of anti-windup with tracking scheme. This is because of the introduction of the gain function, which processes the output of the PI controller.

3.8 CONCLUSION

The integral wind-up problem which occurs in PI controller and the anti-windup technique to overcome it has been explained. The various types of anti-windup schemes viz., back calculation, anti-windup with dead zone,
the anti-windup with tracking and the conditional integration anti-windup
techniques have been studied. The performance of the closed loop chopper
controlled drive system for PMDC motor has been enhanced by implementing
these techniques in the speed control loop. The system has been simulated
with these techniques for the drilling and screwing modes. For various set
speed values the parameters viz., peak overshoot, steady state error and motor
idling time have been found. However wide variations in these parameters
have been observed when the performance comparisons have been made
among the different AWPI techniques taken up for study. The comparative
analysis implies that by using these techniques the steady state and transient
state performance of the system can be improved. In particular, the anti-
windup with tracking shows better performance with reduced peak overshoot
and steady state error. The back calculation and conditional integration anti-
windup schemes provide a moderate performance of reduced peak overshoot
and steady state error. The overall inference is that the closed loop chopper
control drive comprising of anti-windup with tracking provides a better
performance.