Comparison and Evaluation of Anti-windup PI Controllers

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Abstract

This paper presents a comparison and evaluation between different anti-windup proportional-integral (PI) controller strategies used in variable-speed motor drives, and the anti-windup methods are to the speed control of a vector-controlled induction motor driven by a pulse width modulated (PWM) voltage-source inverter (VSI). The simulation results are compared for the different operating conditions and the characteristic of speed response has been analyzed in order to obtain the optimal performance of anti-windup PI controller method.

Keywords: Anti-windup, integrator windup, PI controller, motor drives.

1. Introduction

Recently most variable-speed motor drives system have sought after high performance such as quality and efficiency speed control and fast response time.[1,2] Many of the plant have input limitations. In this case, the real plant input is temporally different form the controller output and the anti-windup phenomenon may occur. Usually, the controller is initially designed to operate in a linear range. When the anti-windup occurs, the close-loop performance will be significantly deteriorated with respect to the expected linear performance such as large overshoot, slow settling time, and sometime instability in the speed response.

In this paper, the anti-windup schemes, for the PI speed control of the induction motor, are compared and evaluated. In addition, a new anti-windup method will be presented. The integral state is separately controlled corresponding to whether the inverter is saturated or not. The simulation results compare the traditional methods, such as conditional integration and tracking back calculation, in order to find which one is more suitable for the induction motor drives.

2. Anti-windup PI control schemes

It is common that the current controller is designed to have much faster dynamics than the speed controller. If a fast current control scheme is employed, the current dynamics is negligible and the variable-speed motor drive can be considered as a first-order system given by

$$\frac{d\omega_r}{dt} = -\frac{1}{\tau_m}\omega_r + k_t v - T_l \tag{1}$$

where $m = J/B$, $k_t = k_T/J$, $T_l = T_L/J$ and v denotes the plant input, namely, the torque-producing current.[2] It is assumed that the plant input v is limited by saturation-type nonlinearity as

$$v = \begin{cases} U_h & \text{if} \quad u > U_h \\ u & \text{if} \quad U_l \le u \le U_h \\ U_l & \text{if} \quad u < U_l \end{cases} \tag{2}$$

where u represents the controller output. In the followings, it will be called as a linear range and a saturation range when $u = v$ and $u \neq v$, respectively.

The PI control law is expressed by

$$u = k_p e + k_i q \tag{3}$$

where k_p, k_i, and k_d denote the proportional, integral, and derivative gains, respectively. The error is

$$e = \omega_r^* - \omega_r \tag{4}$$

where ω_r^* denotes the speed reference. The integral state q is dependant upon the anti-wind controlled methods.

2.1 Conditional integration

Fig.1 shows the PI controller with anti-windup based on the conditional integration.[3] The integral action is switched on or off depending on the linear range or the saturation range such as

$$\dot{q} = \begin{cases} e & \text{if} \quad u = v \\ 0 & \text{if} \quad u \neq v \end{cases} \tag{5}$$

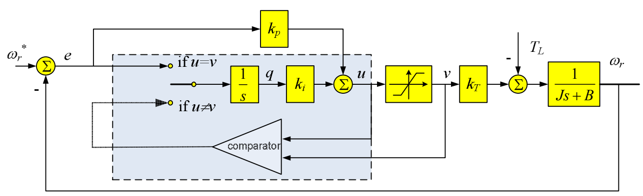


Fig. 1 Conditional integration scheme.

2.2 Tracking back calculation

Fig.2 shows the tracking back calculation method and k_a is called the anti-windup gain.[4] In the linear range, the error is integrated. In the saturation range, difference between the saturated and the unsaturated control signal is used to generate a feedback signal to act on the integrator input.

$$\dot{q} = \begin{cases} e & \text{if} \quad u = v \\ e - k_a(u - v) & \text{if} \quad u \neq v \end{cases} \tag{6}$$

It may seem advantageous to choose a very large value of the anti-windup gain because the integrator is reset quickly. If the anti-windup gain is chosen too big, spurious errors can cause the input saturation, which accidentally resets the integrator. Usually, $k_a = 1/k_p$ is selected.

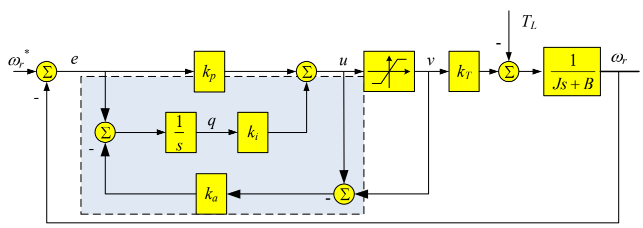


Fig. 2 Tracking back calculation scheme.

2.3 Integral state prediction

Fig. 3 shows the anti-windup PID control with the integral state prediction (ISP) where the single-pole double-throw switch is used

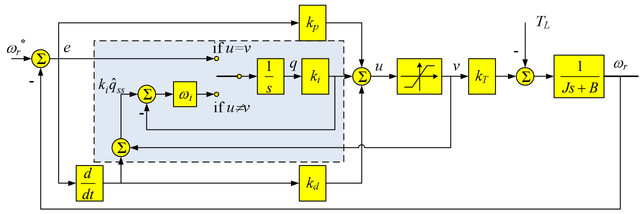


Fig. 3 Anti-windup PID control with integral state prediction.

for the linear and saturated operations.[5] When the PI control operates in the linear range, the output error is connected to the integrator input. When the control operates in the saturation range, the integral state is reset to a predicted steady state value through a low-pass filter to prevent abrupt integral state changing such as

$$\dot{q}=\begin{cases} e & \text{if} \quad u=v \\ \omega_i k_i(\hat{q}_{ss}-q) & \text{if} \quad u\neq v \end{cases} \tag{7}$$

where $\hat{q}_{ss}$ means the final integral state and is predicted by

$$\hat{q}_{ss}=\frac{1}{k_i}\left(\frac{1}{k_t}\left(\dot{e}+\frac{1}{\tau_m}e\right)+v\right). \tag{8}$$

The integral state loading time can be determined by adjusting the parameter ω_i properly. Since the integral state prediction in (8) includes the error derivative, the bandwidth of the low-pass filter is constrained by the derivations. In order to achieve the desired performance dynamics specifications while maintaining closed-loop stability, it is therefore important to select the integral state loading time of the anti-windup PI controller with ISP so that $\omega_i = 1/(0.1T_r)/k_i$.

3. Simulation results

In order to compare the anti-windup PI controller, a speed control of induction motor has been simulated by MATLAB program. Table 1 shows the parameters used for the simulation. Among various anti-windup PI controllers, the conditional integration, tracking back calculation, and proposed ISP schemes are compared.

Fig. 4 shows the responses at no load. It can be seen that the responses of ISP controller and conditional integration controller are similar and the overshoot is better than that of the back tracking controller.

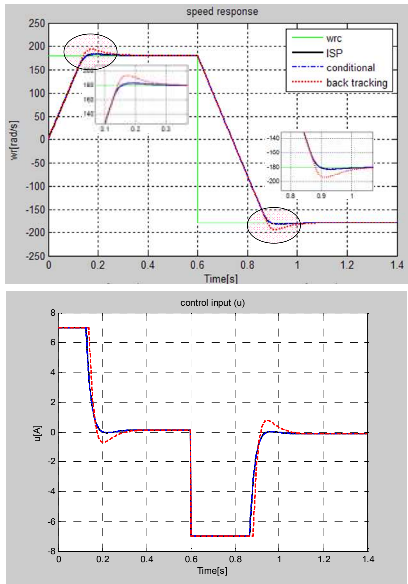
Fig. 5 shows the responses at full load. Both ISP and conditional integration reveal no overshoot, but the conditional integration has more overdamped response. The tracking back calculation has an overshoot response. In view of the responses at load condition, the ISP controller is the most insensitive to load conditions.

4. Conclusion

This paper compares the different anti-windup PI controller applied to the speed control of a vector-controlled induction motor driven by the PWM-VSI. Among the methods, the ISP scheme has much improve the performance such as overshoot and settling time even though the plant input is limited.

Table 1 Parameters for simulation

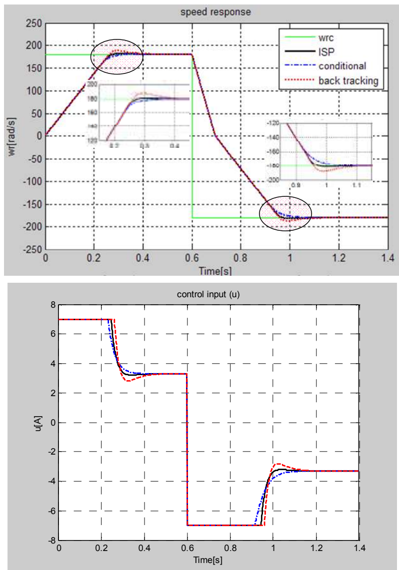
Motor speed	$1730[rpm]$
Rated frequency	$60[Hz]$
Saturation limited range	$[-7,7][A]$
Torque constant (K_T)	$1.3[Nm/A]$
Moment of inertia (J)	$7.1\times10^{-3}[Kgm^2]$
Viscous damping coefficient (B)	$0.96\times10^{-3}[Kgm^2/s]$



(a)

(b)

Fig. 4 Simulation results at no load, (a) speed, (b) control input.



(a)

(b)

Fig. 5 Simulation results at full load, (a) speed, (b) control input.

Acknowledgment

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