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Anti-windup Robust Controller Considering Saturation of Current and Speed for Speed Servo System

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***Abstract*— In general, a speed servo system has a controller with an integrator, such as a PI controller. A robustly stable PI-controller is designed and implemented in order to control the AC motor speed. Wind-up affect due to actuator saturation is removed by implementing anti-windup compensator. When PI controller output variable is saturated by a current and/or voltage limiter, a wind-up phenomenon and an unstable response often occur. We have already proposed an anti-windup algorithm considering voltage saturation for speed servo system that regulates the current response smoothly and stably. Moreover, we considered the saturation of current and speed for position servo system, and the anti-windup algorithm regulated the speed response stably. However, the speed response has the overshoot, which is caused by current saturation and the speed controller not keeping the response performance. This paper proposes an anti-windup algorithm considering the motor dynamics and current saturation for speed servo system of SPM synchronous motor. The experimental and numerical simulation results confirm that the speed servo system having the proposed algorithm regulates the motor speed smoothly and stably.**

Keywords: Anti-windup controller, robust control, Servo Permanent Synchronous Motor, PI controller.

I. INTRODUCTION

A robust servo system is important for improving the performance of motion control systems in several industry applications. A PI controller has been widely used for the speed control of variable-speed motor drives [1]. In this motor drives, a large step change in the speed command will cause the generated current command from the speed controller to exceed the prescribed maximum value and the current command will cause the generated voltage command from the current controller to exceed the prescribed maximum value, which determines the allowable current of the motor and the maximum output voltage of the inverter respectively. Consequently, the PI controller output variable will be saturated by the current and voltage limiters.

This problem may occur because the integral state accumulates control errors even while the output variable saturates, often leading to a wind-up phenomenon. This phenomenon is called integrator windup and can lead to a large overshoot, long settling times and an unstable response. Therefore, a design method for a limitation compensator considering output variable saturation is required. For this several anti-windup control methods have been researched. For example, while the plant input variable is different from the PI controller output variable, a realizable command, instead of the command, is applied to the controller in order to restore the consistency of the integral state [2]. Furthermore, the general framework for the anti-windup design having a co-prime factorization for a feedback controller has been presented [3]. The design criteria are as follows: 1) The nonlinear closed-loop system must be stable; 2) When there is no saturation, the closed-loop performance should meet the specifications for the linear design; and 3) When the saturation occurs, the closed-loop performance should degrade gracefully from the linear performance.

For ideal anti-windup PI control, it is desirable that the control performance satisfies the specifications determined by the PI gains in the linear region. The anti-windup control method considering the vector control condition has been applied to a current controller in order to restore the consistency of the integral state. Furthermore, we have already proposed an anti-windup algorithm considering the saturation of current and speed for position servo system [9]. In addition, we have already proposed a high performance inverter control method considering the motor driving conditions from the shaft acceleration torque command and the omitted voltage caused by voltage saturation [10]. The proposed method combines the advantages of two different over modulation techniques, and obtains both a quick speed response in the transient state and a small value of total harmonic distortion (THD) in the steady state. However, if the inner-loop of the current controller operates at a high performance, the speed response will overshoot owing to current saturation in the outer-loop of the speed controller, and the speed controller will not keeping proper response performance. In order to overcome this problem, this paper proposes a limitation compensator design in order to keep the response performance for speed servo system. This anti-windup algorithm considering motor dynamics and current saturation is applied to the speed controller in order to restore the consistency of the integral state. The simulation results confirm that the speed servo system having the proposed algorithm regulates the motor speed smoothly and stably.

II. SPEED CONTROLLER BASED ON PI CONTROLLER

The block diagram for a speed control system based on a PI controller is shown in Fig.1. The open loop transfer function Gos(s) in this speed control system is defined as

$$\mathrm{Gos}(s) = \frac{\mathrm{sKps} + \mathrm{Kis}}{\mathrm{s}} \frac{\mathrm{Kt}}{\mathrm{sJ}} \qquad (1)$$

where Kps is the proportional gain of the speed controller,and $K$is is the integral gain of the speed controller.

When the angular frequency of the PI corner ωpi is sufficiently smaller than the bandwidth of the speed controller ωsc, the open-loop transfer function Gos(s) in this speed control system is approximated as

$$\mathrm{Gos(s)} \cong \mathrm{Kps} \frac{\mathrm{Kt}}{\mathrm{sJ}} \qquad (2)$$

Kps is calculated such that the open-loop transfer function amplitude becomes one (i.e., /Gos($j\omega$) /= 1). Therefore, Kps and Kis are designed as

$$\mathrm{Kps} = \frac{Jn\ \omega Sc}{Ktn} \qquad (3)$$

$$\mathrm{Kis} = \frac{Jn\ \omega Sc}{Ktn} . \omega pi \qquad (4)$$

where subscript n denotes a nominal parameter. The speed control gain is decided as stated above and can be designed for a speed servo system having arbitrary bandwidth.

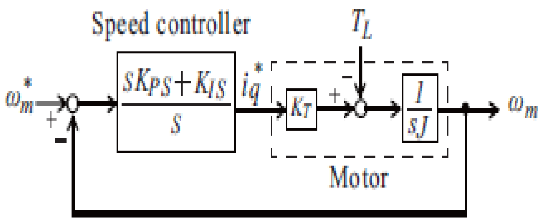


Fig 1: Block diagram of speed control system

The block diagram of a speed servo system based on anti-windup PI controllers are shown below.

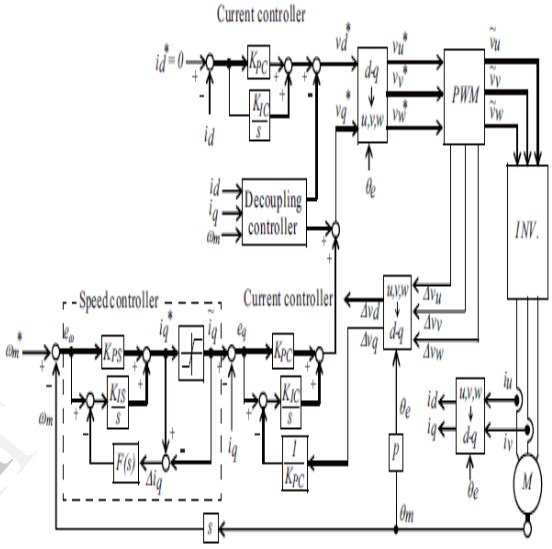


Fig 2: Speed servo system based on anti-windup PI controllers.

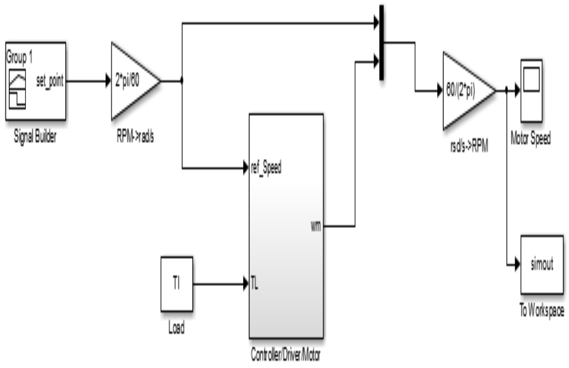


Fig 3: Simulink model of speed servo system based on anti windup PI controllers.

LIST OF MOTOR PARAMETERS AND SPECIFICATIONS OF TESTED SERVO SYSTEM

1. Rated output 200[W]
2. Rated speed 3000[min−1]
3. Rated torque 0.64[Nm]
4. Number of pole pairs 4
5. Inertia 2×10−5[kgm2]
6. Stator resistance 2.47[Ω]
7. Stator inductance 9[mH]

8.	Magnetic flux	0.066[Wb]
9.	q-axis current	2.42[A]
10.	Bandwidth of current controller ωc	3000[rad/s]
11.	Bandwidth of speed controller ωsc	300[rad/s]
12.	Angular frequency of PI corner ω_{PI}	60[rad/s]
13.	Sampling period of current control	100[μs]
14.	Sampling period of speed control	200[μs]

III. ANTI-WINDUP PI CONTROLLER CONSIDERING OUTPUT VARIABLE SATURATION

The equations of a PI controller are defined as

$$y = \frac{sKp+Ki}{s}(u^{*}-u) \qquad (5)$$

where u^* is the command, u is the control variable, and y is the PI controller output variable.

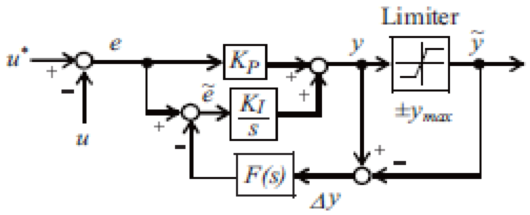


Fig 4: Block diagram of PI controller with limiter

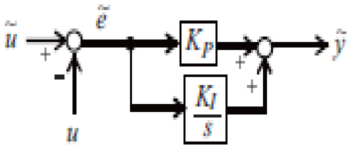


Fig 5: Block diagram of PI controller

When the PI controller output value y exceeds the prescribed maximum value $/ymax/$, the PI controller output value $/y/$ is saturated at the prescribed maximum value $/ymax/$. Then, the PI controller output variable y is approximately equal to the plant input variable $\tilde{y}$. However, when deviation is reduced to almost the same level as the prescribed maximum value $/ymax/$, the PI controller output variable y is not equal to the plant input variable $\tilde{y}$. This problem may occur because the integral state accumulates control errors even while the output variable saturates, often leading to a wind-up phenomenon. Fig.4 shows the block diagram of a PI controller considering output variable y is saturated by using limiter. Then the difference Δy between the controller output variable y and the plant input variable $\tilde{y}$ is calculated. The calculated value is multiplied by the conditioning gain F(s). Then, its calculated value is fed back to the integral state, and the state variable of the PI controller is regulated. Accordingly, occurring of the PI controller output variable prevents integrator windup.

Here, a new PI controller is defined as shown in Fig.5. The PI controller output variable $\tilde{y}$ is not saturated by the limiter, and the equation for $\tilde{y}$ is defined in (6). Moreover, the equation for the control variable u is defined in (7), and the equation for the PI controller is defined in (8).

$$\tilde{y} = \frac{sKp+Ki}{s}(\tilde{u}-u) \qquad (6)$$

$$u = \tilde{u} - \frac{s}{sKp+Ki}\,\tilde{y} \qquad (7)$$

$$y = \frac{sKp+Ki}{s}(u^{*}-u) - \frac{Ki\ F(s)}{s}(y-\tilde{y}) \qquad (8)$$

The command $\tilde{u}$ is expressed by (7) and (8).

$$\tilde{u} = u^{*} - \frac{1}{Kp}\,\frac{s+Ki\ F(s)}{s+Ki/Kp}(y-\tilde{y}) \qquad (9)$$

A. Conventional method

When the conditioning gain (s) = 1/Kps , the PI controller output variable is not saturated by the limiter, and $\tilde{u}$ is expressed as

$$\tilde{u} = u^{*} - \frac{1}{Kp}\,(y-\tilde{y}) \qquad (10)$$

The anti-windup PI controller is applied to the speed controller and the q-axis current controller. The actual motor speed becomes smaller than the speed command owing to the field forcing caused by d-axis voltage saturation [10]. The integral state and the state variable of the PI controller are regulated as

$$y = Kp\ .\ e + \frac{Ki}{S}\,.\,\tilde{e} \qquad (11)$$

$$\tilde{e} = e - \frac{\Delta y}{Kp} \qquad (12)$$

B. Proposed method considering motor dynamics

The design of a limitation compensator considering the motor dynamics and current saturation is detailed in this section. The new conditioning gain F(s) in this design considers the state variable of a PI controller plus the motor dynamics. Accordingly, the speed servo system having the proposed algorithm can keep the response performance of the speed controller. The block diagram converts Fig.4 into Fig.6(a).

In addition, the equivalent block diagram conversion by using block diagram reduction techniques are shown in Fig.6 .

The transfer function $1-H(s)$ is given as

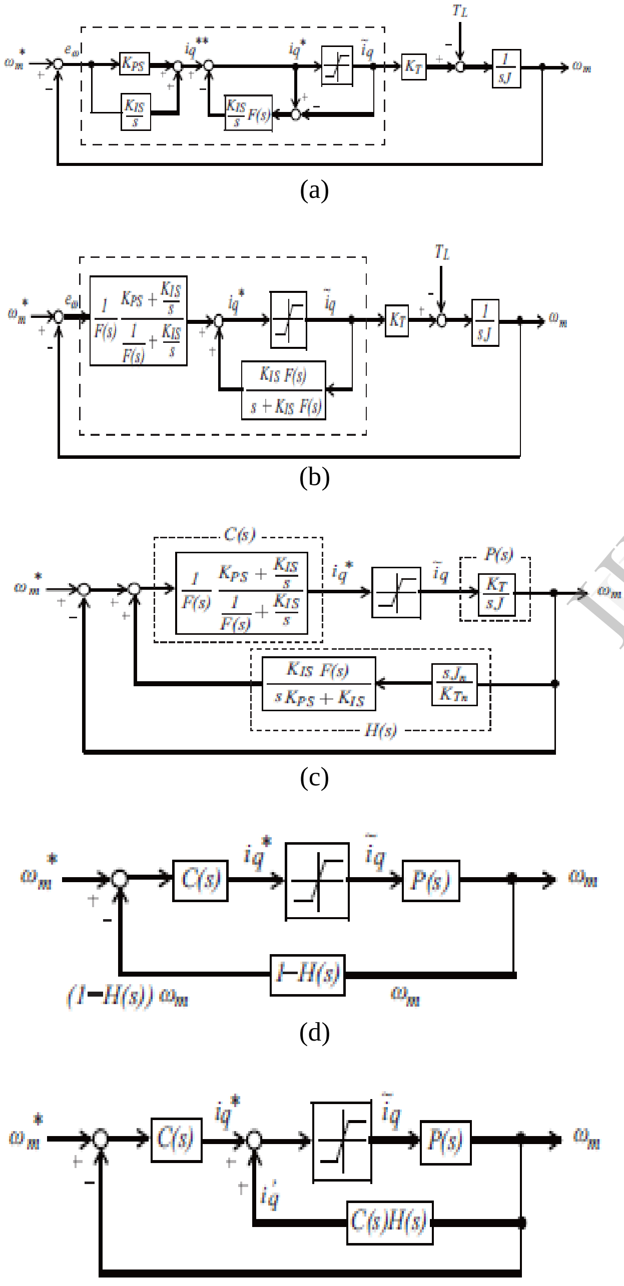
$$1\text{-H(s)} = \frac{1+S\left(\frac{Kps}{Kis} - \frac{Jn}{Ktn}F(s)\right)}{1+\frac{Kps}{Kis}S} \qquad (13)$$

In the conventional method, the speed response will overshoot owing to current saturation and the speed controller not keeping the response performance. Thus, the integral state and state variable of PI controller should be more regulated. The new conditioning gain F(s) is determined under the condition that the numerator of the transfer function $1 - H(s)$ is small. In the proposed method, F(s) is designed under the condition that the numerator of the second term of the transfer function $1 - H(s)$ is zero as

$$s\left(\frac{Kps}{Kis} - \frac{Jn}{Ktn}F(s)\right) = 0 \qquad (14)$$

This implies that

$$F(s) = \frac{\omega sc/\omega pi}{Kps} \qquad (15)$$



(a)

(b)

(c)

(d)

(e)

Fig 6: Equivalent block diagram of PI controller considering with limiter plus motor dynamics

The block diagram of a speed servo system in the proposed method consists of two anti-windup PI controllers. The anti-windup PI controller considering motor dynamics is applied to the speed controller, and the anti-windup PI controller is applied to the q-axis current controller [10].

C. Comparison between proposed and conventional methods

Here, the conditioning gain in conventional method F(s) $=1/KP$ substitutes to the transfer function C(s) and the transfer function $1 - H(s)$ as

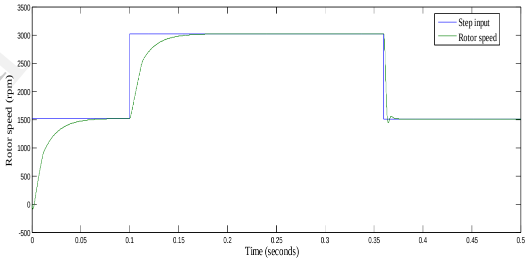
$$C(s) = K_{PS} \qquad (16)$$

The conditioning gain in proposed method F(s) $=\omega sc/\omega p$ Kp substitutes to the transfer function C (s) as

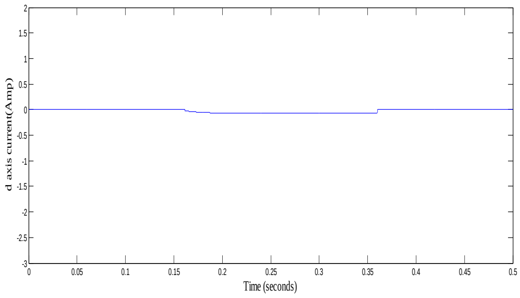
$$C(s) = Kps + \frac{Kis}{s}\left(\frac{s}{s+\omega sc}\right) \qquad (17)$$

Moreover, the equivalent block diagram converts Fig.6(c) into Fig.6(e). The q-axis current $i'qp$ in proposed method is given in (18).

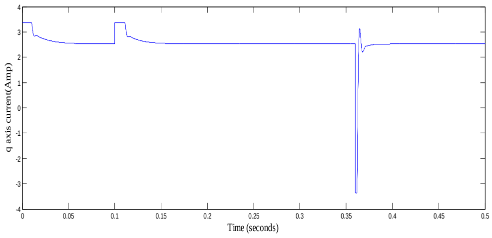
$$i'qp = \frac{Jn}{Ktn}\frac{s\,\omega sc}{s+\omega sc}\,\omega m \qquad (18)$$



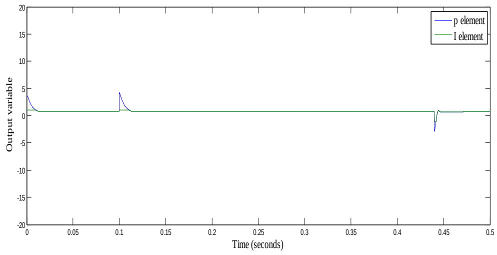
(a). Rotor speed Vs Time



(b). d- axis current Vs time



(c). q- axis current Vs time



(d). output variable Vs time

Fig 7: Simulation results of step speed response

IV. SIMULATION RESULTS

The simulation and experimental results of step speed response of the proposed method as shown in Fig.7 . In conventional method, the speed response has the overshoot caused by current saturation at the deceleration area and the speed controller not keeping the response performance. In contrast, the speed servo system having the proposed anti-windup control method regulates the motor speed smoothly and stably. In addition, the proposed method can keep the response performance of the speed controller and the settling time is shortened. With step load torque, the proposed anti-windup control method regulates the motor speed smoothly and stably. The proposed anti-windup control method regulates the motor speed smoothly and stably.

V. CONCLUSION

This paper proposes a design method for a limitation compensator in order to keep the response performance for speed servo system. The proposed anti-windup algorithm applied to the speed controller considers the motor dynamics and current saturation. In this paper, The simulation results confirm that the proposed method regulates the integral state of the speed controller and the motor speed of the speed servo system smoothly and stably. Hence, the proposed method can keep the response performance of the speed controller and the settling time is shortened.

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