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A Proportional-Feedforward Position Controller Based on Tracking-differentiator of PMSM

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***Abstract*—This paper proposes a proportional-feedforward position controller based on tracking-differentiator for a permanent-magent synchronous motor(PMSM). The proposed position control algorithm can effectively improve the performance of servo system, without producing overshoot. And to further accelerate the response under a wide range of step commands, the saturation of position regulator is utilized to help arranging the transient process of position commands. Simulation results indicate that the designed controller for servo position control system satisfies the designed requirements of fast response without overshoot.**

I. INTRODUCTION

With the development of power electronics technology, computer technology, and automatic control technology, the permanent-magent synchronous motor(PMSM) has been widely used in CNC systems, electric vehicles, robotics, and etc [1]–[2]. Scholars have proposed many position control methods to ensure the steady-state accuracy and the fast response without overshoot of PMSM [3]–[4]. Among which the proportion-feedforward controller can be easily utilized by adding the velocity feedforward control and acceleration feedforward control based on the three feedback control loops. Although it can achieve fast response without steady state error, it would produce overshoot when the range of position step command is too large [5]. In order to avoid overshoot, some scientists adopted tracking-differentior to arrange transient process for position commands [6]–[7]. The position values can then track the commands more smoothly without overshoot. However, when the range of position step command is too small, the response under such kind of controller could be slower than that under the traditional proportion-feedforward controller.

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In this paper, a proportional-feedforward position controller based on tracking-differentiator is adopted to achieve fast response without overshoot in servo position control system. Simulation results verify the feasibility and effectiveness of the proposed method.

II. TRADITIONAL POSITION CONTROL

A. Proportion Controller

PMSM servo system contains three feedback control loops including current loop, speed loop and position loop, where current loop is the inner loop, speed loop and position loop are the outer loops. The bandwidth of the position loop is far narrower than that of the speed loop and the current loop, so that the speed regulator can be equivalent to a first-order inertial link. The proportion controller rather than the proportional-integral controller has been used in the position regulator to ensure that the servo system has no overshoot. Fig.1 shows the block diagram of a servo system with the proportion controller.

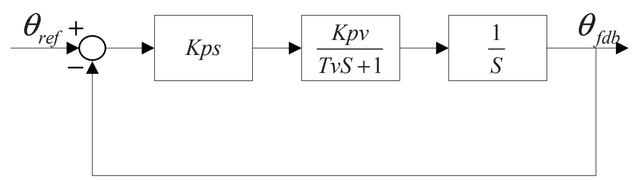

Fig. 1. Block diagram of three loops with proportional controller

where *Kps* is the proportional gain of position regulator, *Kpv* is the proportional gain of speed regulator, *Tv* is inertia time constant of speed regulator, and the PMSM is equivalent to *1/S*.

The open-loop transfer function of the control system is then:

$$H(s) = \frac{K}{S(TvS+1)} \tag{1}$$

where K is the open-loop gain, $K = Kps * Kpv$.

The closed-loop transfer function of the control system is then:

$$\Phi(s) = \frac{K}{TvS^2 + S + K} \tag{2}$$

$$\omega_n = \sqrt{\frac{K}{Tv}}, \qquad \xi_n = \frac{1}{2}\sqrt{\frac{1}{KTv}} \tag{3}$$

where ω_n is the natural angle frequency, ξ_n is the damping ratio.

Unfortunately, the open loop transfer function of control system is the typical I system, which uses the proportion controller that would produce steady-state error according to the S curve [8]. Furthermore, the control system requires no overshoot so that the damping ratio $\xi_n \geq 1$, the open-loop gain $K \leq \frac{1}{4Tv}$. From the equation $K \leq \frac{1}{4Tv}$, it is concluded that overshoot and response speed of the system could not be satisfied at the same time .

B. Proportion-Feedforward Controller

To reduce the steady-state error and improve control performance, the proportion-feedforward control is usually applied for the position control. Fig.2 shows the block diagram of three feedback control loops with proportion-feedforward controller.

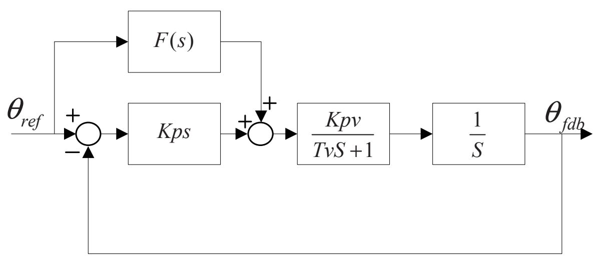

Fig. 2. Block diagram of three loops with proportional-feedforward controller

where *F(s)* is the feedforward transfer function. The closed-loop transfer function of proportion-feedforward controller is then:

$$\Phi(s) = \frac{F(s) \cdot \frac{Kpv}{S(TvS+1)} + \frac{Kps \cdot Kpv}{S(TvS+1)}}{1 + \frac{Kps \cdot Kpv}{S(TvS+1)}} \quad (4)$$

In theory, the closed-loop transfer $\Phi(s) = 1$ when $F(s) \cdot \frac{Kpv}{S(TvS+1)} = 1$. The output of the system can entirely track the position commands and the system has ideal response. The feedforward transfer function is then:

$$F(s) = \frac{Tv}{Kpv} S^2 + \frac{1}{Kpv} S \quad (5)$$

F(s) is made up of two parts: the feedforward value of speed and the feedforward value of acceleration. Although it can lead to zero steady-state error and the good tracking performance when the system is running at a constant speed, it can produce overshoot when the range of position step command is too large.

III. TRACKING-DIFFERENTIOR

It can avoid the overshoot by using the tracking-differentiator to arrange transient process for step commands.

The discrete form of the second-order is that:

$$\begin{cases} x_1(k+1) = x_1(k) + h \cdot x_2(k) \\ x_2(k+1) = x_2(k) + h \cdot u, |u| \leq r \end{cases} \quad (6)$$

Professor Han proposes and verifies the discrete form of steepest tracking-differentiator for the second-order discrete system as follows [9]:

$$\begin{cases} fh = fhan(x_1(k) - v_0(k), x_2(k), r, h) \\ x_1(k+1) = x_1(k) + h \cdot x_2(k) \\ x_2(k+1) = x_2(k) + h \cdot fh \end{cases} \quad (7)$$

where $v_0(k)$ is input signal at k sampling time, x_1 is the output signal, x_2 is differential output signal, h is integration step.

Steepest control integrated function $u = fhan(x_1, x_2, r, h)$ is presented as follows:

$$\begin{cases} d = r \cdot h \\ d_0 = h \cdot d \\ y = x_1 + h \cdot x_2 \\ a_0 = \sqrt{d^2 + 8 \cdot r \cdot |y|} \\ a = \begin{cases} x_2 + \frac{a_0 \cdot d}{2} sign(y), |y| > d_0 \\ x_2 + \frac{y}{h}, |y| \leq d_0 \end{cases} \\ fhan = \begin{cases} r \cdot sign(a), |a| > d \\ r \cdot \frac{a}{d}, |a| \leq d \end{cases} \end{cases} \quad (8)$$

$$r = \frac{4}{T_0^2}$$

where r is acceleration factor, T_0 is step response time.

A large amount of experiments show that the appropriate transition process can effectively solve the contradiction between the overshoot and the fast response of servo system. The steepest tracking-differentiator can achieve filtering if the input signal $v_0(k)$ with the noise [10].

IV. THE PROPOSED METHOD

The block diagram of position regulator with proportional-feedforward controller is shown in Fig.3.

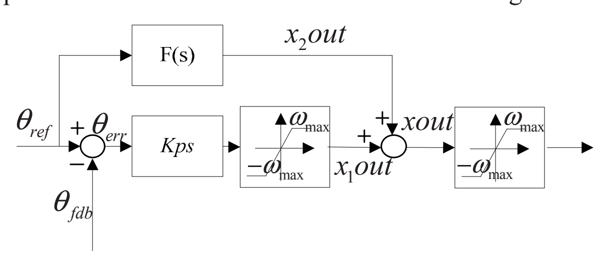

Fig. 3. Block diagram of position regulator with proportional-feedforward controller

The discrete form of position regulator is shown as (9), (10), (11):

$$\begin{cases} x_1out = K_{ps}\theta_{err}, |x_1out| < \omega_{\max} \\ x_1out = \omega_{\max}, x_1out \ge \omega_{\max} \\ x_1out = -\omega_{\max}, x_1out \le -\omega_{\max} \end{cases} \quad (9)$$

$$\begin{aligned} x_2out &= K_{vu}(\theta(k)-\theta(k-1)) \\ &+K_{au}(\theta(k)-2\theta(k-1)+\theta(k-2)) \end{aligned} \quad (10)$$

$$\begin{cases} xout = x_1out + x_2out, |xout| < \omega_{\max} \\ xout = \omega_{\max}, xout \ge \omega_{\max} \\ xout = -\omega_{\max}, xout \le -\omega_{\max} \end{cases} \quad (11)$$

where x_1out is the output of proportional regulator, x_2out is the output of feedforward regulator, $xout$ is the output of position regulator, $\omega_{\max}$ is the maximum speed of PMSM, K_{vu} is the equivalent gain of speed feedforward regulator, K_{au} is the equivalent gain of acceleration feedforward regulator.

In formula (9), the error θ_{err} between the reference position command θ_{ref} and the feedback position θ_{fdb} is so large that the output of proportional regulator x_1out can reach the limit value $\omega_{\max}$ when the range of position step command is too large. No matter how large the output of feedforward regulator x_2out is, the output of position regulator $xout$ can reach the limit value $\omega_{\max}$ in formula (11). Therefore the control performances of the proportion--feedforward controller and the proportion controller are the same. Both of them have overshoot for the step commands.

It can avoid overshoot by using tracking-differentior to arrange transient process for position commands, but it may also reduce the speed of response. However, when the position regulator is not saturated, response by using tracking-differentior to arrange transient process is not faster than that of the proportion-feedforward controller.

In order to satisfy the fast response without overshoot, a proportional-feedforward position controller based on tracking-differentiator is proposed. The block diagram shows in Fig.4.

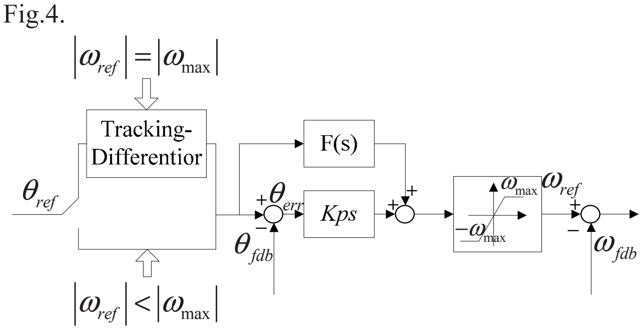

Fig. 4. Block diagram of proportional-feedforward position controller based on Tracking-differentiator

The proposed controller would arrange transient process for position commands according to the saturation of the position regulator as Fig.4 shows. When $|\omega_{ref}|$ is less than $|\omega_{\max}|$, which means the position regulator is not saturated, it uses the proportion-feedforward controller to satisfy fast response. The feedback position θ_{fdb} can well track the reference position command θ_{ref} with the effect of the proportion-feedforward controller. The error θ_{err} is zero in steady state. But if the step command is too large, $|\omega_{ref}|$ is equal to $|\omega_{\max}|$, which means the position regulator is saturated. The proportion-feedforward controller lost the ability to control the position loop that would produce overshoot and oscillation. In order to solve the problem, transient process by using tracking-differentior would be arranged.

V. The Simulation Results

In order to verify the efficiency of the proposed controller, the closed-loop control system of PMSM is built on the platform of MATLAB/Simulink. Parameters of PMSM used in the simulation are given as follows:

TABLE I
THE PARAMETERS OF PMSM

Parameter	Value
Rated current	6.5A
Rated voltage	310V
Rated speed	2000r/min
Rated torque	16N.m
Armature resistance	1.6Ω
Armature inductance of d axis	16.03mH
Armature inductance of q axis	17.15mH
Rotor flux linkage	0.16Wb
Rotor inertia	$1.1*10^{-3}$kg.m^2
Number of poles	3

Fig.5 shows the proportional controller response curve when the position step command is 15rad. Fig.6 shows the proportional-feedforward controller response curve when the position step command is 15rad.

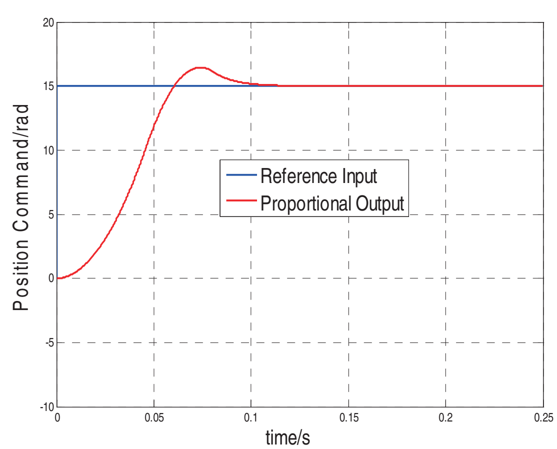

Fig. 5. Proportional Controller Output at 15 rad

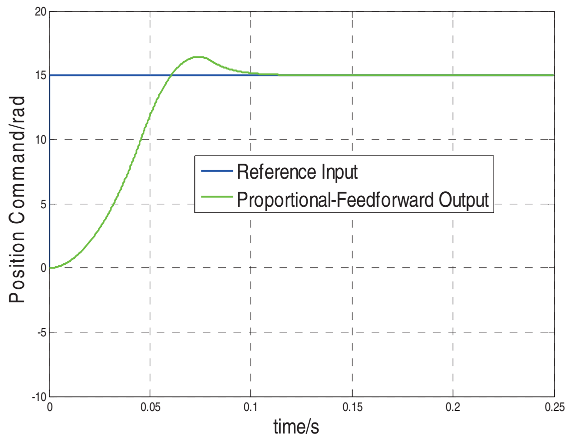

Fig. 6. Proportional-Feedforward Controller Output at 15 rad

It can be seen that the performance of the proportional controller and the proportional-feedforward controller are the same from Fig.5 and Fig.6. Both of them produce overshoot that is 9.67%. The position regulator is saturated now.

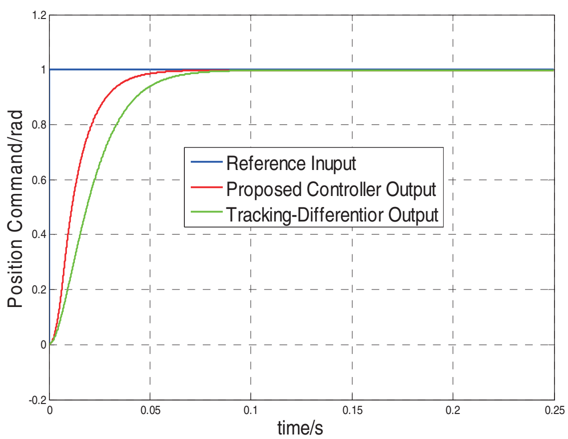

Fig. 7. The Proposed Controller Output and The tracking-differentior Output at 1 rad

Fig.7 shows the proposed controller response curve and the tracking-differentior controller response curve when the position step command is 1rad.

The rising time of the proposed controller is 0.0285s and the rising time of tracking-differentior is 0.0435s from Fig.7. It can be concluded that the response of proposed controller is faster than tracking-differentior controller at one rad. The position regulator is not saturated, where the proposed controller is equivalent to the proportional-feedforward controller now.

Fig.8 shows the proposed controller response curve and the proportional-feedforward controller response curve when the position step command is 15rad.

The proposed controller has no overshoot at 15rad, but the proportional-feedforward controller produces overshoot which is 9.67% from Fig.8. The position regulator is saturated, where the proposed controller is equivalent to the tracking-differentior controller now. The performance of the proposed controller is better than the proportional--feedforward controller.

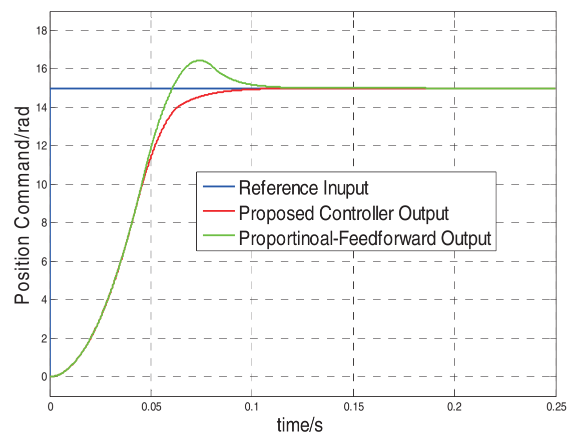

Fig. 8. The Proposed Controller Output and The Proportional-Feedforward Controller Output at 15 rad

VI. Conclusion

Considering the requirement of fast response without overshoot for PMSM, the traditional proportional--feedforward controller and the tracking-differentiator controller are analyzed first in this paper. It is concluded that the proportional-feedforward controller could produce overshoot for the wide range of step commands and the tracking-differentiator controller may reduce the speed of response. To resolve the conflict between overshoot and response speed, this paper proposes the proportional-feedforward position controller based on tracking-differentiator which can arrange transient process for position commands according to the saturation of the position regulator. As a result, the overshoot of the servo system is eliminated and the response speed is faster.

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