Design and Simulation of Variable Structure PI Controller

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Abstract. Aiming at the poor performance of IP control system in tracking continuously varying input signals, a variable structure PI controller was proposed, which can eliminate overshoot of step response and track continuously varying input signals without error. The controller performs as an IP controller for step input signals and a PI controller for continuously changing input signals. Firstly, the control performance defects of traditional IP controller were analyzed, and then the structure of variable structure PI controller was built. Finally, the simulation results show that the VSPI and IP control systems have the same control effect when the step signal is input. Compared with PI control system, the VSPI and IP control systems not only have no overshoot but also have better response stability. When the input is a continuous sinusoidal signal, VSPI and PI can track the input signal almost without error, and the control effect is obviously better than IP control. The anti-jamming performance of the system is inversely proportional to the bandwidth value, but has nothing to do with the control mode.

1. Introduction
When the speed loop of permanent magnet synchronous motor is controlled by PI, the output response will overshoot for step input. As a result, document [1] uses the method of arranging transition process to eliminate overshoot, but the form of process function is complex; document [2] uses output differential negative feedback to reduce overshoot, but this method increases measurement noise due to the use of differentiators. For this reason, the pseudo-differential feedback control and IP control methods proposed in [3] and [4,5] are essentially identical, both of which can suppress overshoot of step response well, but at the same time, the steady-state error of input response with continuous variation will be increased. The traditional controller only considers the condition of step input signal. When the input signal is continuously changing, it needs to be redesigned. Although IP controller can eliminate overshoot of step response, it also makes tracking performance worse. In order to improve the adaptability of the controller to various inputs, a variable structure PI controller is proposed in this paper. It can automatically select different control modes according to different types of input signals to achieve optimal control.

2. IP Controller
The speed loop IP controller using the pre-stop integral anti-saturation method [6] is shown in Figure 1 below.
As can be seen from Figure 1, the expression of the control quantity of the system is as follows:

\[ i^* = \frac{\dot{\Omega} - k_{ps}y_s + k_{is}\int (\Omega^* - y_s)dt}{b_s} \]  

(1)

In the formula, \( k_{ps} \) is the proportional coefficient of the controller; \( k_{is} \) is the integral coefficient of the controller, \( b_s \) is the control gain, \( i^* \) is the given value of the cross-axis current, \( \Omega \) is the mechanical angular velocity, and \( y_s \) is the measured value of the mechanical angular velocity.

Regardless of the effects of feedback speed filtering, current loop bandwidth and control saturation, formula (1) is substituted into the state equation of angular velocity of the mechanism, and the output of the system is as follows:

\[ \Omega(s) = \frac{s^2 + k_{is}}{s^2 + k_{ps} + k_{is}} \Omega^*(s) + \frac{s}{s^2 + k_{ps} + k_{is}} d_i(s) - \frac{k_{ps}s + k_{is}}{s^2 + k_{ps} + k_{is}} \delta_n(s) \]  

(2)

The current amplitude and bandwidth of the current loop are limited, so when the step signal is input, its input differential is a pulse signal, and the system does not respond to the signal, resulting in the input differential feed-forward being basically ineffective. The output of the system will be changed to:

\[ \Omega(s) = \frac{k_{is}}{s^2 + k_{ps} + k_{is}} \Omega^*(s) + \frac{s}{s^2 + k_{ps} + k_{is}} d_i(s) - \frac{k_{ps}s + k_{is}}{s^2 + k_{ps} + k_{is}} \delta_n(s) \]  

(3)

It can be seen from equation (3) that the system is a typical second-order system. \( s^2 + k_{ps}s + k_{is} \) is the characteristic polynomial \( s^2 + 2\zeta\omega_n s + \omega_n^2 \) of the typical second-order system, then \( k_{ps} = 2\zeta\omega_n \), \( k_{is} = \omega_n^2 \), \( \omega_n \) is the natural frequency without damping and \( \zeta \) is the damping ratio.

As long as the value of the damping ratio is greater than 1, the step response of the system can be achieved without overshoot. Compared with the step response of the system, there will be overshoot in the PI controller under any damping condition, which is obviously more advantageous in suppressing overshoot.

But when the input signal changes continuously, the input differential feed-forward can take effect because the system can respond to the differential of the signal. Formula (2) shows that there are steady-state errors in the IP control system at this time. Compared with the PI control system which continuously tracks the change of input signal without error, its control performance is worse than that of the PI control system.

### 3. Variable Structure PI Controller

Based on the defect of the above IP control system in tracking continuously varying input signals[7][8], a new variable structure controller is proposed. Its control structure is shown in Figure 2 below. The system is an IP controller when the step signal is input, and a PI controller when the continuous change signal is input. Therefore, the system can not only eliminate the overshoot of the step response, but also track the continuous change of the input signal accurately.
If the input is a step signal, the control quantity generated by the given differential term is large, which will lead to saturation in the first cycle. At this time, the integral input is zero, and the anti-integral saturation algorithm takes effect[9] [10]. Since the given differential term after the second cycle is zero, the control quantity will not be saturated. The output of the corresponding adder is the input of the integral link [11], and the controller can be equivalent to the control structure shown in Figure 3 below.

![Figure 3](image)

**Figure 3** Equivalent structure of VSPI with step input

### 4. Simulation Analysis

Next, in order to verify the effectiveness of the proposed controller, the response characteristics and stability of the controller under the action of step signal and sinusoidal signal are simulated and analyzed respectively.

#### 4.1 Step Signal Action

No-load startup experiments of VSPI, PI and IP control systems with input step signals of 80rpm and 800rpm are carried out respectively. The output dynamic response waveforms are shown in Figure 4.

From the graph, the dynamic response curves of VSPI and IP control systems basically coincide. Compared with PI control system, the response of VSPI and IP control systems is not only non-overshoot, but also more stable.

![Figure 4](image)

(a) Dynamic response at 80 rpm  
(b) Dynamic response at 800 rpm

**Figure 4** Dynamic response of no-load starting at 80rpm and 800rpm

In order to further verify the effect of system bandwidth $\omega_n$ on speed response, it is assumed that the step input signal is 800rpm and the system bandwidth $\omega_n$ is 80, 160 and 320, respectively. The final speed response curve is shown in Figure 5.

Obviously, the larger the value of $\omega_n$, the better the response speed and tracking performance of the system. In this case, the rapidity and overshoot are mutually unified [12].
4.2 Sinusoidal Signal Action
The no-load start experiments of VSPI, PI and IP control systems under sinusoidal input signal are carried out. The amplitude of the signal is 500 rpm, the frequency is 5 Hz, and the $\omega_n$ is 80. The response waveform is shown in Figure 6.

From the graph, the error ranges of VSPI and PI control are 5 rpm and 6 rpm respectively. The speed response curves of VSPI and PI control coincide almost completely, while the response error range of IP control is 340 rpm, so VSPI and PI control are obviously better than IP control.

4.3 Anti-jamming Analysis
In order to test the anti-jamming performance of VSPI control system, when the system runs stably at 800 rpm, the bandwidth $\omega_n$ is 80 and 160, respectively. The unloading experiment of the system is carried out. The loading curve is shown in Figure 7 below, and the response waveform is shown in Figure 8 below.

It can be seen from the graph that the larger the value of $\omega_n$, the smaller the fluctuation of speed caused by load, the smaller the anti-interference performance, but the greater the system noise [13].
Figure 8 Unloading dynamic response under different $\omega_n$

In order to verify the anti-jamming performance of three different control systems, taking $\omega_n$ as 80, three different control systems are loaded according to the curve shown in Figure 7, and their respective response waveforms are shown in Figure 9. From the graph, when the bandwidth $\omega_n$ is the same, the response curves of the three control systems almost coincide, which shows that the anti-jamming performance of the three control systems is the same when the bandwidth is the same.

Figure 9 Unloading dynamic response of three control systems under the same $\omega_n$

5. Concluding Remarks
In order to obtain the optimal control effect under the action of multiple input signals, this paper designs a variable structure PI control based on the principle of traditional IP control, which effectively solves the contradiction between overshoot and rapidity of step response, and greatly improves the tracking performance of continuous change input response. The controller has simple structure design, convenient parameter setting and can adjust the control law adaptively according to different types of input speed signals. Finally, the comparative simulation results verify the superiority of the variable structure PI control proposed in this paper, which opens up new methods and ideas for the speed servo system of high performance permanent magnet synchronous motor.

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