A New Anti-Windup PI Controller for Direct Torque Control System

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Abstract

Speed controller in induction motor direct torque control (DTC) system usually adopts the traditional PI controller. But the traditional PI controller has characteristic of nonlinear saturation, what will make the control performance of actual system become worse. In order to improve system control performance, this paper adopts a new type Anti-Windup PI controller. This method separately control the integral state by feedbacking the output of the integrator to the input port of the integrator according to whether the controller output is saturated or not, which can make the system leaving saturation as soon as possible. As a result, the overshoot and settling time of the system are reduced. Simulation and experimental results show that this method can significantly suppress the integral windup phenomenon as well as reduce the overshoot and shorten the settling time. The new Anti-Windup PI controller has a better performance than the traditional PI controller.

Key words: induction motor; direct torque control; PI controller; Anti-Windup; simulation

1. Introduction

Direct torque control (DTC) technology is a high-performance AC speed regulating technique. It appears later than the vector control technology. But compared with vector control technology, DTC technology will not be restricted by current regulator bandwidth. So the torque dynamic response is faster and not sensitive to the change of the parameters of motor [1-5]. But a typical speed controller of DTC system usually uses PI controller. While the traditional PI controller does not consider the upper limit of actual torque. When the mutation in the speed is happened, PI controller will output a big torque. But actually the motor can’t output such a big torque. It will make the performance of the system become worse. We call this phenomenon Windup [6-10].

To solve this problem, this paper adopts a new type Anti-Windup PI controller. The new controller can quickly exit the saturated zone, So as to realize the reducing of overshoot and faster response speed [11-14].

2. New Anti-Windup PI Controller

In the induction motor, the relationship between speed and torque is:

$$\frac{d\omega}{dt} = \frac{(T_e^* - T_L)}{J} - \frac{\omega}{J/B}$$

(1)

Using s-function can be expressed as:

$$\omega = \frac{(T_e^* - T_L)}{Js + B}$$

(2)

In the equation, $\omega$ is angular velocity of the mechanical rotor, $J$ is the moment of inertia of the motor, $B$ is the Viscous friction coefficient, $T_e^*$ is the given torque of the motor, $T_L$ is the
load torque, \(J/B\) is called the mechanical time constant. Let \(k_m=J/B\), that is to say \(k_m\) is mechanical time constant.

Traditional PI controller is affected by the Windup phenomenon, its equivalent on the output side joined a limiting function \(T_E^*(u)\). Equation (3) is the expression. Figure 1 is the function of the corresponding curve. Figure 2 is the PI controller structure with a saturation limit.

\[
T_E^*(u) = \begin{cases} 
T_{\text{max}} \cdot \text{sgn}(u) & |u| > T_{\text{max}} \\
\frac{1}{u} & |u| \leq T_{\text{max}}
\end{cases}
\]

(3)

In this equation, \(u\) is the output of traditional PI controller, \(\text{sgn}(u)\) is the sign function.

To inhibition the saturation phenomenon, this article introduced a new type Anti-Windup PI controller, figure 3 shows the control block diagram. According to the Figure 3, When \(u = T_E^*\), switch \(S_1\) will be closed, \(S_2\) will be opened. The controller turns into the typical PI controller. When \(u > T_E^*\), switch \(S_2\) will be closed, \(S_1\) will be opened. The output multiplied by a coefficient and then negative feedback to the input. So that the integral output can converges to zero rapidly.
The $i$ in Figure 3 is integral state. Its expression is:

$$i = \begin{cases} \frac{K_i}{s} e, & u_s = u_n \\ -\frac{i}{k}, & u_s \neq u_n \end{cases} \quad (4)$$

In Equation (4), $K_i$ is integral constant. $k$ is the integral feedback gain coefficients. And $k$, $K_i << k_m$.

3. Stability Analysis

If the system is stable, the system must meet two conditions. First the system in the linear region is stable. Second the system could convergence to the linear area from the saturated zone. If two conditions are satisfied at the same time, the system will be stable.

3.1. First Condition

In the linear, the new Anti-Windup PI controller is the same as traditional PI controller. At this time the error can be expressed as:

$$\dot{e} = \frac{\omega'}{k_m} - \frac{(i - T_L)}{J} - \frac{1 + K_i}{k_m} e \quad (5)$$

Lyapunov function is defined as follow:

$$L_i(e, i) = \frac{1}{2} \left( J e^2 + \frac{(i - i_0)^2}{K_i} \right) \quad (6)$$

In the Equation (6), $i_0$ is $i$'s stable value, so:

$$L_i(e, i) = e \left( (B \omega' + T_L) - i_0 \right) - (B + \frac{K_i}{J}) e^2 \quad (7)$$

$$i_0 = B \omega' + T_L \quad (8)$$

In the linear, it always meets:

$$\begin{cases} \dot{V}_2(e, q) \leq 0 \\ i_0 \leq T_{\text{max}} \end{cases} \quad (9)$$

To sum up, the controller’s stable condition in the linear is:

$$|T_L| + B |\omega'| \leq T_{\text{max}} \quad (10)$$

3.2. Second Condition

In the saturated zone, we can get the expression of error from Equation (1).

$$\dot{e} = -\frac{e}{k_m} - \frac{(T_L^* - T_L)}{J} + \frac{\omega'}{k_m} \quad (11)$$

From equation (4) we can get:

$$i = -\frac{i}{k} \quad (12)$$
Because of $k << k_m$, the dynamic speed error is far slower than the integral dynamic state. That is to say, the integral state $i$ was immediately set to zero when the controller is in the saturated zone. So:

$$
\begin{align*}
    u &= K_p e + i \\
    &= K_p e \\
\end{align*}
$$

(13)

If $E_b = \frac{T_{max}}{K_p}$. From Equation (13), we can find that, when $|e| \leq E_b$ the controller is in the linear, when $|e| > E_b$ the controller is in the saturated zone.

Lyapunov function is defined as follow:

$$
L_2(e) = \frac{e^2}{2}
$$

(14)

After the derivation:

$$
\begin{align*}
    \dot{L}_2(e) &= e \times \dot{e} \\
    &= \frac{e^2}{k_m} + \left[ \frac{\omega^*}{k_m} - \frac{(T_e - T_L)}{J} \right] e \\
\end{align*}
$$

(15)

Take Equation (2) and Equation (13) into Equation (15)

$$
\begin{align*}
    \dot{L}_2(e) &= \frac{e^2}{k_m} - \frac{T_{max}}{J} \left[ \frac{\omega^*}{J} + \frac{T_{max}}{k_m} \right] e \\
    \leq &\frac{e^2}{k_m} \left[ \frac{\omega^*}{k_m} - \frac{(T_{max} - |T_e|)}{J} \right] e \\
\end{align*}
$$

(16)

Because of $\dot{L}_2(e) \leq 0$, only need to meet:

$$
|e| \leq k_m \left( \frac{1}{J} (T_{max} - |T_L|) + |\omega^*| \right)
$$

(17)

So we can get the condition:

$$
|T_e| + B |\omega^*| \leq T_{max} + \frac{B}{K_p} T_{max}
$$

(18)

Compared Equation (10) and Equation (18), we can see that as long as the system meet Equation (10) must meet Equation (18). So Equation (10) is the stable condition.

To sum up we can get the stable condition as follow:

$$
|T_e| + B |\omega^*| \leq T_{max}
$$

(19)

4. Modeling and Simulation

Matlab/Simulink is used to carry out the modeling and simulation. Figure 4 is the structure chart of the DTC system with the new Anti-Windup PI controller. First of all, according to Figure 4 the model of induction motor DTC system with traditional PI controller was established. And then the model of the new Anti-Windup PI controller was established, shown in
the Figure 5. Finally the new Anti-windup PI controller replaced the traditional PI controller, so that we can get two different simulation diagrams of speed response.

![Figure 4. The Structure Chart of the System](image)

![Figure 5. The New Anti-Windup PI Controller Simulation Diagram](image)

5. Simulation and Experiment

5.1. The Simulation Results

Motor parameters are listed as follows: the stator resistance $R_s=2.5\Omega$, the rotor resistance $R_r=2.7\Omega$, the stator inductance $L_s=0.3325mH$, the rotor inductance $L_r=L_s=0.3325mH$, the mutual inductance $L_m=0.3194mH$, the logarithmic $P=2$, the moment of inertia $J=0.0086kg.m^2$. PI parameters is same in the two controllers, $K_p=1$, $K_i=10$. The integral feedback gain coefficients in the new Anti-Windup PI controller is $k=0.95$. The maximum output torque of the motor is $T_{max}=10N.m$, discrete sampling period is $50\mu s$. The stator flux linkage given value is $\psi^*=0.8Wb$.

Induction motor is starting with no load, but the load torque will become $4N.m$ at $1s$. Speed is $0$ at the beginning, then step to $400rad/s$ at $0.1s$. Figure 6 is the results of simulation graphs. Figure 7 and Figure 8 are the partial enlarged figures.

From Figure 7 we can see that, traditional PI controller’s overshoot amount of speed response reached $17.5\%$ and adjustment time is $0.6s$, but the new Anti-Windup PI controller is almost no overshoot amount of speed response and adjustment time is only $0.25s$. From the simulation results can be seen, the new Anti-Windup PI controller’s control performance has very obvious advantage.

From Figure 8 we can see that, when the load turns into $4N.m$, the two curves are similar. Two types of controller’s ability to resist load disturbance is almost the same.
5.2. Experimental Result

On the basis of theoretical analysis and digital simulation, this article has carried on the corresponding experimental research. Experiment system adopts the special motor control digital signal processor TMS320F2812 as the controller. Processor TMS320F2812 with RS - 232 serial communication ports will be collected experimental data transmitted to the PC.

The motor parameters are the same. The stator flux linkage amplitude to 0.8 Wb. Speed given value for 50 rad/s = 477.5 r/min. The load is about 1 N.m.

Figure 9 to 10 are the experimental results. The experimental results and simulation results are consistent. It validates the correctness of this method.
6. Conclusion

The traditional PI controller has integral saturation problem, so this paper adopts a new type Anti-Windup PI controller. And the condition for the stability of the system is given. Simulation and experimental results show that, the new Anti-Windup PI controller can reduce or even eliminate overshoot amount of speed response, and shortens adjusting time. At the same time, the controller also has the advantages of simple structure and easy to project implementation.

References