An Improved PI Regulator Based on Parameter Identification of IPMSM

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Abstract. With the extensive application of permanent magnet synchronous motor in the new energy vehicle industry, the requirements of manufacturers for motor speed control and torque response performance are also more stringent. However, the inductance parameters of the motor will change in real time as the current changes, which will affect the responsiveness and stability of the control. Based on the simplest PI regulator, this paper presents a method to identify the parameters of permanent magnet synchronous motor (PMSM) and uses this parameter to improve the regulator.

1. Introduction
With the advantages of high efficiency, high power density and high torque density, permanent magnet synchronous motor has attracted more and more attention in the rapid development of power electronics technology, especially in the new energy vehicle industry. The traditional gasoline engine has small torque at low speed, and the diesel engine has a poor performance at high speed. Although the engine and transmission match, to some extent, alleviate this problem, but it brings problems of poor smoothness and low efficiency. At the same time, the thermal conversion efficiency of the traditional internal combustion engine is only 30%~40%, while the efficiency of PMSM can basically stay above 90%, and the peak efficiency can even reach over 98%. In addition, permanent magnet motor can ensure maximum torque output at low speed, and maximum power output at high speed, these features promote the rapid development of electric vehicles [1, 2, 3].

In the commonly used vector control strategy in engineering, the performance of the current loop in the inner loop directly affects the response to the commands of the torque loop and the speed loop. Therefore, the calibration of the current loop adjuster parameter is very important, and the motor permanent magnet flux linkage and d, q-axis inductance directly affects the current loop parameters. In this paper, using the simplified mathematical model of permanent magnet synchronous motor, combined with the output of the system current loop integral term, the permanent magnet flux linkage of the motor and the corresponding cross-axis inductance under different d and q axis currents are measured in offline mode. Change the parameter used in the actual conditions of the motor current loop adjustment. And then adjust the current loop of the actual condition of the parameters used in the motor.

2. PMSM model
The diagram 1 shows the physical model of the permanent magnet synchronous motor [4]. Ignoring the effect of magnetic field saturation, hysteresis, harmonic back EMF and eddy current loss, etc., we can get the stator voltage vector equation in ABC three-phase stationary coordinate system as follows(Eq.1):
Through Clark transformation and Park transformation, the basic voltage equation can be converted to the synchronously rotating d/q reference frame \([5, 6]\). During the operation of the motor, if the influence of temperature and other factors is ignored, the permanent flux can be regarded as a constant, so the relationship between the d/q-axis voltage and the d/q-axis current of the PMSM could be expressed as Eq.2.

\[
\begin{align*}
    u_d &= R_s i_d + L_d \frac{di_d}{dt} - \omega_r L_q i_q \\
    u_q &= R_s i_q + L_q \frac{di_q}{dt} + \omega_r L_d i_d + \omega_r \psi_f
\end{align*}
\]

3. Principle of parameter identification

The widely used PI regulator in motor control system is simple in structure, and it is a linear regulator in principle. Increasing proportional gain can increase the response speed, but it will cause large overshoot with the increase of proportion coefficient, which will affect the stability of the system \([7]\).

The traditional current loop can be implemented with the simplest and most intuitive PI regulator, and the control block diagram is shown as figure 2. The PI regulator only considers the first two items in the Eq.2, and regards the item related to the speed as external disturbance. Moreover, the disturbance can be regarded as a fixed value under the steady state of the motor. In the engineering implementation, the structure can be realized by Eq.3 to complete the system's current Closed-loop control.
\[
\begin{aligned}
U_{p1} &= K_p1(i_{dref} - i_{dfdb}) \\
U_{l1} &= K_i1(i_{dref} - i_{dfdb}) + U_{l1-1} \\
u_q^* &= PI_{dout} = U_{p1} + U_{l1} \\
U_{p2} &= K_p2(i_{qref} - i_{qfdb}) \\
U_{l2} &= K_i2(i_{qref} - i_{qfdb}) + U_{l2-1} \\
u_d^* &= PI_{qout} = U_{p2} + U_{l2}
\end{aligned}
\] (3)

Where \(i_{dref}\) and \(i_{qref}\) are the reference of d- and q-axis components of armature current. \(i_{dfdb}\) and \(i_{qfdb}\) are the feedback of d- and q-axis components of state current, these variables are converted from three-phase phase current collected by a sampling circuit. \(K_p1, K_p2, K_i1, K_i2\) are the ratio coefficient and the integral coefficient of d- and q-axis adjustor. \(U_{p1}, U_{p2}, U_{l1}, U_{l2}, PI_{dout}, PI_{qout}\) are the proportion, integral and output value after each calculation of the regulator. \(U_{l1-1}, U_{l2-1}\) are the integral value in the last calculation period. \(u_d^*, u_q^*\) are the expected value of d- and q-axis components of terminal voltage.

In the dynamic process, the expected voltage is the sum of the proportional term and the integral term. In the steady state, the current feedback is the same as the given current, so the proportion term is 0, in other words, \(u_d^*, u_q^*\) are equal to the output of the integral term.

In equation (2), stator resistance \(R_s\) is a milli-ohm coefficient, so \(R_s i_d\) and \(R_s i_q\) terms can be regarded as 0. \(i_d\) is constant \(i_{dref}\) and \(i_q\) is constant \(i_{qref}\) at steady state, so \(di_d/dt\) and \(di_q/dt\) are 0, thus \(L_d(di_d/dt)\) and \(L_q(di_q/dt)\) can be regarded as 0. Therefore, we get the following equation in the steady state.

\[
\begin{aligned}
u_d^* &= U_{l1} = u_d = -\omega_r L_q i_q \\
u_q^* &= U_{l2} = u_q = \omega_r L_d i_d + \omega_r \psi_f
\end{aligned}
\] (4)

That is, in the steady-state, d-axis integral output is related to the amount of q axis current and inductance, and the q-axis of the integral output for a related quantity d axis current, inductance and the permanent magnet flux.

4. Parameter Measurement and PI Improvement

When the current Closed-loop is realized by the traditional PI in the control system, the d- and q-axis current can be tracked in the steady state. At this point, drag to a fixed speed \(\omega\), given \(i_{dref}=0\) and \(i_{qref}=0\). From (4), \(u_d\) is 0, and \(u_q\) is \(\omega_r \psi_f\) in the steady state. Compared with equation (3), \(\omega_r \psi_f\) is equal to the value of the integral term \(U_{l2}\) in the regulator, so \(U_{l2} = \omega_r \psi_f\). Now, the rotational speed is known, and the permanent magnet chain can be obtained as follows:

\[
\psi_f = \frac{U_{l2}}{\omega_r}
\] (5)

Add the calculated flux link to the system, the regulator of q-axis becomes as equation (6), and the control block diagram becomes as shown in figure 3.

\[
u_q^* = PI_{qout} = U_{p2} + U_{l2} + \omega_r \psi_f
\] (6)

In the adjusted system, change the given current to \(i_{dref}=A\) and \(i_{qref}=0\). From (4), \(u_d\) is 0, and \(u_q\) is \(\omega_r L_d i_d + \omega_r \psi_f\) in the steady-state. Compared with equation (6), \(U_{p2}\) is 0 because of the steady state, and \(\omega_r \psi_f\) has been compensated by the previous operation, so \(U_{l2} = \omega_r L_d i_d\). Now, the rotational speed and d-axis stator currents are known, so the d-axis stator inductances can be obtained as follows:
\[ L_d = \frac{U_{i2}}{\omega_r i_d} \quad (7) \]

Change the given current to \( i_{d\text{ref}} = 0, \ i_{q\text{ref}} = A \). From (4), \( u_d \) is \(-\omega_r L_q i_q\), and \( u_q \) is \( \omega_r \psi_f \) in the steady-state. Compared with equation (6), \( U_{i1} \) is \(-\omega_r L_q i_q\) under these circumstances. Because speed and \( q \)-axis stator currents are known, so the \( d \)-axis stator inductances can be found by equation (8).

\[ L_q = \frac{U_{i1}}{\omega_r i_q} \quad (8) \]

*Figure 3. Improved PI of Q-axis*  
*Figure 4. Improved PI of Current-loop*

By this method, the flux of permanent magnet can be measured. By selecting different \( A \) values, we can get the corresponding \( L_d \) under different \( i_d \) and the corresponding \( L_q \) under different \( i_q \). The \( d \)- and \( q \)-axis inductance after the measurement is processed into the software and used as the table of the inductor at different \( d \)- and \( q \)-axis current in the motor working. Finally, the regulator of the current loop is shown as follows and the control block diagram show as figure 4.

\[
\begin{align*}
    u_d^* &= U_{p1} + U_{i1} - \omega_r L_q i_q \\
    u_q^* &= U_{p2} + U_{i2} + \omega_r L_d i_d + \omega_r \psi_f
\end{align*}
\quad (9)
\]

In the whole adjustment process, the integral term of the improved current loop can be guaranteed to be basically 0, thus the response of the system is enhanced and the overshoot of the system is reduced. The response speed of the current loop can be further accelerated when the compensating term current is replaced by the given current value in the regulator.

5. Simulation and Experimental Verification

The simulation model of the system is built by Simulink to verify the improved control system. The torque command changes from 0NM to 100NM at 1000rpm with the same PI parameter, figure 5 is the original system and figure 6 is the system that measuring parameters and applying them to PI regulation through the above method. The comparison shows that the response speed of the improved system is doubled, and the overshoot is reduced nearly 50%.

In experimental condition, a prototype of 60kW IPMSM (Figure.7 gives its detailed parameters) is used, cooperating with the DSP MPC5744P, complete monolithic resolver-to-digital converter AD2S1210 and IGBT 2MBI450VN-120-50 (repetitive peak reverse voltage 1200V and Continuous DC forward current 450A) to implement the proposed control technique. The controller hardware is shown as shown in the diagram 8.
Experiments were performed on an AVL bench with a DC bus voltage of 600V, the stable output of the peak torque (750NM) below the rated speed (1300rpm) and the maximum power (100KW) output at the peak speed (4000rpm) are achieved. On this basis, the current loop PI regulator before and after the improvement were tested. Before the improvement, the traditional PI regulator can be used as the current inner loop to achieve the steady state output of the above indexes as well, but the premise is that the mutation of the current instruction cannot be too large. Because in the absence of compensation, a large instruction switching regulator needs a certain time to respond to achieve stability. Long time error accumulation will also cause greater concussion. With the above method, a set of inductors is measured at each interval of 20A between 0 and 300A. Linearization between adjacent two points for the basis of the system compensation term lookup table. And the measurement results are shown in Figure 9.

When the new PI regulator is received the new current instruction, the compensation term can be added to the corresponding value instantaneously, so the integral term only needs to be trimmed in a small tuning in the vicinity of 0 to ensure the current tracking. It brings a better dynamic response and a significant decrease in current shock. Fig. 10 shows the three-phase phase current response waveform of the improved system at 6K switching frequency and at 600rpm when the torque command is directly added to 600NM from 0NM, and the RMS of phase current reaches 290A. The adjustment process only uses the 750ms to realize the torque response of the 600NM, and the overshoot is small, basically without concussion, and the three-phase symmetry is good.

The curve in figure 11 shows the output of the PI regulator and the output of the integral term when the system is 3000rpm, with different winding currents. The integral term is always very small, and it is adjusted in the range of ±5%, which is consistent with the theory.
6. Conclusion
In this paper, an improved PI regulator based on the parameter identification of IPMSM is introduced. The parameter identification method relies on the integral term of the PI regulator and then applies the identified parameters to the compensation term of the PI regulator, so that the integral term of the current loop during tuning is substantially zero. Significantly improved system responsiveness and reduced overshoot and oscillation of the system.

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