Optimization of vector control torque ripple of permanent magnet synchronous motor based on internal model principle

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Abstract. Due to the dead zone effect caused by the non-ideal device of inverter, the currents of the quadrature and straight axis in the synchronous rotation coordinate of permanent magnet synchronous motor (PMSM) contain a large number of harmonic components, resulting in violent torque harmonics. Based on the field weakening control in single current regulator of interior permanent magnet synchronous motor (IPMSM), this paper gives an analysis of the reason for speed fluctuation, and a novel current compensation control strategy based on internal model control is proposed. By this means, the influence of harmonic currents on electromagnetic torque can be reduced meanwhile the advantage of single current regulator in filed weakening control is fully exploited. The feasibility and effectiveness of the proposed scheme are evaluated by Simulation analyses and experimental results.

1. Introduction

MTPA control has been widely concerned by scholars due to the limitation of current vehicle battery capacity. However, due to the factors such as flux saturation, slot effect and inverter nonlinearity during motor operation, IPMSM reverse electromotive force will be non-sine [1-4]. The defect of motor torque ripple caused by this seriously affects the control performance of IPMSM in electric vehicle.

Literature [5] proposed a harmonic current injection method through the analysis of motor torque fluctuation. Since this method requires an accurate motor model, it is greatly affected by motor parameter error, which is not conducive to engineering implementation. Literature [6] introduced the iterative learning controller into the motor speed control to effectively suppress the periodic fluctuations in the motor operation. Literature [7] proposed a voltage vector compensation scheme by judging the polarity of phase current. When the motor is running at a low speed, there will be errors in judgment of phase current polarity due to the small current, thus affecting the actual control effect.

In order to give full play to the performance of permanent magnet synchronous motor (PMSM) in MTPA control strategy, the torque ripple caused by the increase of inverter output harmonic due to dead zone effect and zero-current clamping effect is suppressed. Based on the analysis of the cause of motor torque ripple, an internal model control strategy is adopted to add a dead zone compensation controller to the original control system. The defect of torque ripple is improved when the motor is running at the working point of low speed under the MTPA control strategy. Finally, the validity of this method is verified by MATLAB simulation and actual motor running.
2. Cause analysis of MTPA control torque ripple

2.1. IPMSM mathematical model and MTPA control.

The static stator terminal voltage equation of permanent magnet synchronous motor in synchronous rotating coordinate system is adopted [8,9]

\[
\begin{align*}
\begin{cases}
u_d = R_d i_d - w_e L_d i_q \\
u_q = R_q i_q + w_e L_d i_d + w_r w_f
\end{cases}
\end{align*}
\]  

(1)

Where, \(i_d, i_q\) are stator current of straight-quadrature axis; \(u_d, u_q\) are stator voltage of straight-quadrature axis. \(L_d, L_q\) direct-quadrature axis stator inductance; \(w_r\) for permanent magnet magnetic chain; \(w_e=\frac{n_p}{w_r}, n_p\) is polar logarithm and \(w_r\) is mechanical angular velocity.

The torque equation of permanent magnet synchronous motor is:

\[
T_e = \frac{3}{2} p_a [\psi_f i_q + (L_d - L_q) i_d i_q]
\]

(2)

2.2. IPMSM torque ripple cause

In the control of space voltage vector modulation (SVPWM), the factors causing the distortion of the output waveform of voltage source inverter (VSI) include the dead zone time \(T_d\) inserted by human, the power tube switch delay \(T_{on}, T_{off}\), the power tube opening voltage drop \(v_t\), the following diode opening voltage drop \(v_d\), etc.

VSI one PWM cycle time is \(T_{pwm}\). According to the principle of area equivalence, the inverter output error voltage \(\Delta u\) waveform can be expressed by formula (3)

\[
\Delta u = \left[\frac{T_d + T_{on} + T_{off}}{T_{pwm}} (U_{dc} + v_q - v_r) + \frac{v_r + v_t}{2}\right] \text{sign}(i_a), \text{sign}(i_a) = \begin{cases} 1, i_a > 0 \\ -1, i_a < 0 \end{cases}
\]

(3)

The Fourier transform of \(\Delta u\) is as follows:

\[
u_{err} = \frac{4\Delta U}{\pi} \left(\sin(\omega t) + \sum_{n=3k+1}^{\infty} \frac{1}{n} \sin(n\omega t)\right)
\]

(4)

\(\Delta U\) is the amplitude of \(\Delta u\). Because the motor stator windings are connected in a star connection, the inverter only has 5, 7, 11...The subharmonic components affect the torque ripple. By ignoring the high-order harmonics and only considering the influence of 5, 7, 9 and 11 harmonics, the VSI output \(u_a, u_b, u_c\) phase harmonic voltages \(u_{a,corr}, u_{b,corr}, u_{c,corr}\) will lead to the stator current producing corresponding harmonic components. Due to the current harmonic generated by inverter, the torque equation of permanent magnet synchronous motor in equation (2) becomes:

\[
\begin{align*}
T_{c,1} &= \frac{3}{2} p_n \left[\psi_f i_{q1} + (L_d - L_q) i_{d1} i_{q1}\right] \\
T_{c,5} &= \frac{3}{2} p_n \left[\psi_f + (L_d - L_q) i_{d1}\right] (i_{s5} + i_{q5}) \\
T_{c,12} &= \frac{3}{2} p_n \left[\psi_f + (L_d - L_q) (i_{s5} + i_{q5})\right] (i_{s5} + i_{q5})
\end{align*}
\]

(5)

Where, \(i_{d1}, i_{q1}\) are the fundamental wave components of the d-q axis current; \(i_{s5}, i_{q5}, i_{d7}\) and \(i_{q7}\) are the fifth and seventh harmonic components of the d-q axis stator current. It can be seen that the \(T_{c,1}\) terms are dc variables and generate constant torque without causing torque ripple. In terms of \(T_{c,5}\), all variables are trigonometric functions with a frequency of \(6w\), thus causing the 6th harmonic of torque output of permanent magnet synchronous motor. Similarly, all variables in the \(T_{c,12}\) term are trigonometric functions whose frequency is \(12w\), thus causing the 12th harmonic of torque output of permanent magnet synchronous motor.
3. MTPA control torque ripple suppression and strategy optimization

3.1. Optimization of traditional MTPA control strategy by internal model principle

As shown in figure 1, in the PMSM double closed-loop vector control system adopting the traditional maximum torque current ratio control strategy, the current inner loop regulator usually adopts the proportional integral control mode. The dead zone time of IGBT is usually set as 2~10us according to the performance of the selected power components, and the influence of dead zone time can be ignored when the motor runs normally. However, when the motor is operated at a low speed and light, due to the low output voltage of the inverter, the higher the carrier frequency is, the greater the proportion of dead zone time in a cycle will be. At this time, the dead zone effect of the inverter will lead to the increase of harmonic proportion in the motor’s working current, and the motor will have a larger torque ripple and a higher copper loss when it is running at a low speed.

![Figure 1. Block diagram of traditional MTPA control system](image)

The improvement and optimization of this scheme lies in that the current controller in traditional MTPA control system basically adopts PI control. Although the dc component of the system can be tracked without static difference, it can be seen from formula (5) that due to the dead zone effect of the inverter, there are still a large number of harmonics with frequencies of $6\omega$ and $12\omega$ in the control system. According to the principle of internal model control, the harmonic components of the $6\omega$ and $12\omega$ frequencies that dominate the system harmonics in the alternating and direct axis current are separately suppressed and compensated, and a proportional resonance (PR) harmonic compensation controller is designed to suppress the motor stator current fluctuation, as shown in figure 2 below:

![Figure 2. Proportional resonance (PR) harmonic compensation controller](image)

In order to enhance the stability of the proportional resonance controller, an improved proportional resonance controller is adopted in this paper, and its transfer function is shown in formula (6):

$$G_{pr}(s) = \frac{2k_w \omega_s}{s^2 + 2\omega_s + \omega_0^2}$$

Let the quantities $i_d^*$ and $i_q^*$ be 0. $\omega_0$ is resonance frequency, $\omega_c$ is cut-off frequency, and $k_r$ is resonance coefficient. In this paper, the motor stator current harmonic suppression controller adopts a new compound proportional resonance control strategy. The ac harmonic component of the stator current and the stator dc component of the motor in the synchronous rotating coordinate system are independently controlled in different control loops. The gain of $G_{pr}(s)$ is $k_r$ at resonant frequency,
while the gain at other non-resonant frequency is basically zero. Therefore, the current controller can realize zero steady-state error control of reference value and suppress harmonic interference.

3.2. Control simulation of MTPA torque ripple suppression

Based on the above analysis, in order to verify the effectiveness of the new torque fluctuation scheme proposed in this paper under the MTPA control strategy based on the principle of internal model control, the simulation was carried out in MATLAB/Simulink. The motor simulation parameters and the dead zone time and tube pressure drop parameters of VSI simulation are set according to the MOS tube IRFS431 parameters selected in the actual test bench as shown in table 1 below.

| Parameter              | Value          |
|------------------------|----------------|
| Pole-pairs $p_n$       | 6              |
| dc inductance $L_d / mH$ | 15.25          |
| ac inductance $L_s / mH$ | 72             |
| Conduction pressure drop $u_t/V$ | 1.3    |
| Stator resistance $R_s / \Omega$ | 14.25 |
| Flux linkage $\varphi_f / W_b$ | 19.78 |
| Rotational inertia $kg \cdot m^2$ | 2.13   |
| Dead band time $T_d/\mu s$ | 4     |

In order to compare the effectiveness of the scheme, the simulation waveform of a permanent magnet synchronous motor with a given speed of 1000r/min and PR resonance control under no load was firstly tested, as shown in figure 3.

![Simulation Waveform](image)

Figure 3 $n^\prime = 1000r/min, T_e = 0N \cdot m$ simulation waveform

It can be seen from figure 3 (a) and (b) that before the resonance suppression designed in this paper was added, the stator current of permanent magnet synchronous motor was obviously harmonic and distorted due to the influence of inverter dead zone effect, which directly affected the stability and comfort of electric vehicle when running at high speed. Compared with figure 3 (c) and (d) of the motor speed waveform, it can be clearly seen that, due to the influence of current harmonic and distortion, the speed fluctuates greatly before resonance suppression is added, and the motor speed is obviously improved after resonance suppression.

In order to better compare the effectiveness of the design scheme in this paper, figure 4 shows the simulation waveform of the motor with load. $T_e = 10N \cdot m$ for a given load at 0 ~ 0.15s, and $T_e = 30N \cdot m$ for a load at 0.15 ~ 0.3s. According to the analysis in figure 4 (a) and (b), the improved design scheme in this paper can not only effectively suppress the current harmonic generated by the dead zone effect, but also realize effective following of the given motor torque and smaller torque fluctuation. By comparing the motor speed waveform before and after compensation in figure 4 (c) and (d), the optimization scheme proposed in this paper can effectively suppress the motor speed fluctuation.
4. Experimental results and analysis

Based on the analysis of simulation results, the effectiveness and reliability of the proposed speed fluctuation suppression scheme are further verified. The reliability of this scheme is verified by a 7.5kw permanent magnet synchronous motor test platform. The IPMSM test platform and IPMASM controller are as follows.

The test system mainly includes a permanent magnet synchronous motor controller with TMS320F28335 as the core, a built-in permanent magnet synchronous motor and DW160 motor test bench. The motor tester is set to work in the constant torque mode, and the motor speed and stator current RMS can be monitored through the upper computer in real time. Before and after using the design scheme in this paper, the motor stator current waveform is shown in figure 6.
By comparing the FFT analysis spectrum of (c) and (d) measured stator current waveform of the motor in figure 6, it can be seen that there are 5 and 7 harmonics of higher components in the stator current caused by inverter nonlinear factors before the system compensation, and the THD values of current harmonics are respectively 43.21% and 24.37%. After adopting the resonance compensation control algorithm designed in this paper, the proportion of the seventh harmonic component decreased significantly, and the current harmonic THD value decreased to 3.16% and 12.53% respectively.

5. conclusion
In this paper, an improved structure based on the original MTPA control strategy is proposed to effectively suppress the torque ripple of permanent magnet synchronous motor in the low-speed operating region. On the one hand, it can make full use of the maximum torque current ratio to control the motor under the same stator current to output the maximum torque. On the other hand, through the analysis of the dead zone effect of the inverter, the resonance control scheme proposed effectively inhibits the influence of harmonic voltage and torque ripple when the motor is running at low speed, plays a better role in suppressing the influence of the sixth harmonic in the motor torque, and improves the control performance of the permanent magnet synchronous motor. Simulation and bench test results show the effectiveness of the improved control scheme.

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