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A Flux Weakening Control Algorithm Based on Notch Filter

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Abstract

In order to solve the problem that the SVPWM over modulation caused the fluctuation of steady-state speed in the flux weakening region of surface-mounted permanent magnet synchronous motor (PMSM), by analyzing the mechanism of the leading angle flux weakening control algorithm, the conclusion is that the sixth harmonic of inverter output voltage caused by SVPWM over modulation which is transmitted to the d-q reference currents through the flux weakening voltage close-loop deteriorates the current and speed control performance. A notch filter is designed in the voltage close-loop to filter the sixth harmonic component of the input voltage signal, meanwhile the other signal components are not affected. The experiment results show that, after adding notch filter, the sixth harmonic component of the input voltage signal is significantly reduced and the current waveforms are remarkably improved, so that the flux weakening speed control performance is effectively enhanced.

Keywords: *surface-mounted permanent magnet synchronous motor, SVPWM over modulation, leading angle flux weakening control, sixth harmonic, notch filter*

1. Introduction

High-speed, high-precision permanent magnet synchronous motor(PMSM) is one of the core components of high-level CNC machine tool, which is widely used in the field of aerospace, automotive, precision instruments and mould manufacturing [1]. As CNC machine tools manufacturing the work piece, it requires not only a large output torque of PMSM at low speed to meet the fast starting, acceleration and other requirements, but also a good speed performance in flux weakening region. Therefore, PMSM can run steadily with wide speed range in the case of limited inverter capacity.

SVPWM over modulation control is often used to improve the utilization ratio of inverter output voltage when PMSM is in flux weakening region [2, 3]. But it will cause the decrease of the pulse number of inverter output voltage, thus the times of chopper will reduce in a sinusoidal cycle and the low order harmonic components of output voltage will increase. These harmonic components can make the input signal of current loop composite a certain frequency AC signal through the flux weakening voltage close-loop, and consequently there will be positive feedback of current loop and current oscillation to cause the system instability, meanwhile the speed control capacity of PMSM in flux weakening region will decline seriously.

To improve the speed performance of PMSM in flux weakening region, scholars have conducted many control methods, such as adaptive flux weakening control [4], direct torque control [5], flux weakening control based on a reduced-order controller [6], flux weakening control based on imaginary instantaneous power theory [7, 8] and so on. Unfortunately, these methods are all complicated and difficult to realize. Some improved methods are also presented based on these control strategies. For example, the flux weakening control algorithm using the difference between d-q currents and voltage outer-loop output to correct the command current is proposed in reference [9], a simplified flux weakening voltage control algorithm is proposed in reference [10], and reference [11] conducts a leading angle flux weakening control method. However, the study on how to eliminate the influence on speed performance in flux weakening region by the low order harmonic components of SVPWM over modulation is relatively less.

In this paper, based on the leading angle flux weakening control algorithm, a notch filter is designed in the voltage close-loop to filter the sixth harmonic component of the input voltage

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signal, meanwhile the other signal components are not affected. The experiment results show the effectiveness of this method.

2. The Mathematical Model of PMSM

In d-q axis, the stator voltage equation of surface-mounted PMSM is:

$$\begin{cases} u_d = R_s i_d + L_d \dfrac{di_d}{dt} - \omega_r L_q i_q \\ u_q = R_s i_q + L_q \dfrac{di_q}{dt} + \omega_r L_d i_d + \omega_r \psi_f \end{cases} \tag{1}$$

Where i_d and i_q are the d-q axis stator currents, L_d and L_q are the inductances of d-q axis stator coil. For surface-mounted PMSM, L_d=L_q. R_s is the phase resistance of stator, ω_r is the rotor electrical angular velocity, ψ_f is the magnetic linkage of permanent magnet.

When PMSM is at high speed, the stator voltage can be ignored, and the voltage equation can be regarded as:

$$\begin{cases} u_d = -\omega_r L_q i_q \\ u_q = \omega_r L_d i_d + \omega_r \psi_f \end{cases} \tag{2}$$

As the stator voltage $u_s = \sqrt{u_d^2 + u_q^2}$, from equation (2) we can get:

$$u_s = \omega_r \sqrt{\left(L_q i_q\right)^2 + \left(L_d i_d + \psi_f\right)^2} \tag{3}$$

As shown in Equation (3), the excitation magneto-motive force is produced by the permanent magnet and cannot be adjusted. When above the base speed, as the output of current regulator exceeding inverter's DC bus voltage which will cause the current regulator saturation, the flux-weakening control is necessary. The speed ω_r is raised without breaking the voltage balance by increasing the direct axis demagnetization current i_d and reducing the cross axis current i_q.

3. The Leading Angle Flux Weakening Control Algorithm

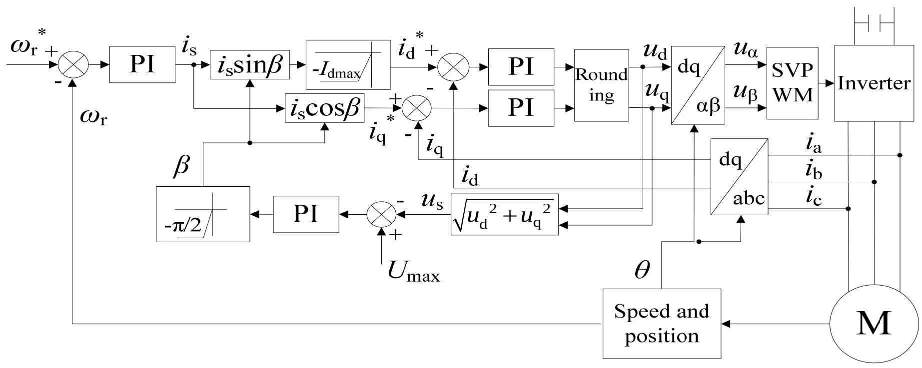


Figure 1. Block Diagram of Leading Angle Flux Weakening Control Algorithm

Figure 1 shows the block diagram of leading angle flux weakening control algorithm. The basic principle is that the output of current loop is regarded as the input of voltage PI regulator in the control circuit, and the difference between the given voltage U_{max} and $\sqrt{u_d^{\ 2}+u_q^{\ 2}}$ is used to generate the leading angle β between stator current vector and q-axis through the voltage PI regulator. U_{max} is $U_{dc}/\sqrt{3}$, and U_{dc} is the DC bus voltage of the inverter. When u_s is less than U_{max}, due to the saturation element in PI regulator, the PI regulator is in positive saturation and the leading angle β = 0. As a result, i_d = $i_s \sin\beta$ = 0 and PMSM runs in constant torque region. When u_s is higher than U_{max}, the input of PI voltage regulator is negative. The PI regulator begins to withdraw from the saturated state, and the leading angle β is negative ($-\pi/2 \le \beta < 0$). As a result, i_d is also negative and PMSM runs in flux weakening region. At the same time, i_d should be limited less than the maximum demagnetizing current of PMSM.

In the leading angle flux weakening control algorithm, SVPWM over modulation control is often used to improve the utilization ratio of inverter DC bus voltage and the voltage output ability, so that the fluctuation of current is reduced in the dynamic process of speed response. Based on the principle of the voltage source inverter, there are not even harmonic and three harmonic in the inverter output voltage. The harmonic proportional in voltage signal generated by SVPWM over modulation will increase with the rising of modulation ratio [12, 13]. When the six-step mode is reached, the A-phase voltage is:

$$U_a = U_1 \cos\omega_r t + U_5 \cos 5\omega_r t - U_7 \cos 7\omega_r t + ... \tag{4}$$

In Equation (4), U_1 is the amplitude of fundamental component of stator voltage signal, U_5 and U_7 are the amplitude of fifth and seventh harmonic components. As the amplitude of higher harmonic component is small, so the harmonic components contained in the voltage signal is mainly fifth and seventh harmonics.

The stator voltage is transformed from ABC three-phase axis to d-q two-phase axis. From Equation (5)~(7), through Clark&Park transform, the fifth and seventh harmonic components of ABC three-phase voltage are transformed to sixth harmonic component of d-q voltage. As a result, the current loop output u_d and u_q contain sixth harmonic component.

$$\begin{bmatrix} u_{d,6} \\ u_{q,6} \end{bmatrix} = T \begin{bmatrix} U_5 \cos(5\omega_r t + \varphi_5) + U_7 \cos(7\omega_r t + \varphi_7) \\ U_5 \cos(5\omega_r t + \varphi_5 + 120^\circ) + U_7 \cos(7\omega_r t + \varphi_7 - 120^\circ) \\ U_5 \cos(5\omega_r t + \varphi_5 + 240^\circ) + U_7 \cos(7\omega_r t + \varphi_7 - 240^\circ) \end{bmatrix} \tag{5}$$

In Equation (5), T is the transformation matrix of Clark&Park.

$$T = \begin{bmatrix} \cos\omega_r t & \cos\left(\omega_r t\text{-}120^\circ\right) & \cos\left(\omega_r t\text{-}240^\circ\right) \\ -\sin\omega_r t & -\sin\left(\omega_r t\text{-}120^\circ\right) & -\sin\left(\omega_r t\text{-}240^\circ\right) \end{bmatrix} \tag{6}$$

From Equation (5) and Equation (6), we can get:

$$\begin{bmatrix} u_{d,6} \\ u_{q,6} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} U_5 \cos\left(6\omega_r t + \varphi_5\right) + U_7 \cos\left(6\omega_r t + \varphi_7\right) \\ -U_5 \sin\left(6\omega_r t + \varphi_5\right) + U_7 \sin\left(6\omega_r t + \varphi_7\right) \end{bmatrix} \tag{7}$$

According to the leading angle flux weakening control algorithm mentioned in literature [14], the flux weakening controller is designed in Figure1. In the over modulation region, the rounding of u_d and u_q which contain sixth harmonic component can be regarded as the actual voltage vector, so u_s also contains sixth harmonic component which exists in u_d and u_q. It is transmitted to the d-q reference currents i_d^* and i_q^* through the flux weakening voltage close-loop. In the current loop, this sixth harmonic component may cause the positive feedback of current loop and deteriorate the current control performance. Therefore, as PMSM running with load in constant power region, the speed and torque will oscillate and the speed control performance is affected, even the system will be instability.

The sixth harmonic component is the main harmonic component of u_d and u_q in the over modulation phase. In order to avoid the impact on the current loop and the speed performance and as much as possible retain the real voltage signal in addition to the sixth harmonic, a notch filter is designed in the voltage close-loop to filter the sixth harmonic component of input voltage signal, meanwhile the other signal components are not affected. The notch filter is designed by all-pass filter in this paper.

4. Flux Weakening Control Algorithm Based on Notch Filter

In the signal processing system, notch filter is often utilized to filter out the signal of one or more periodic interference, and the other frequency components are not affect. Notch filter is actually a band-stop filter with narrow bandwidth [15, 16]. Block diagram of notch filter is shown in Figure 2.

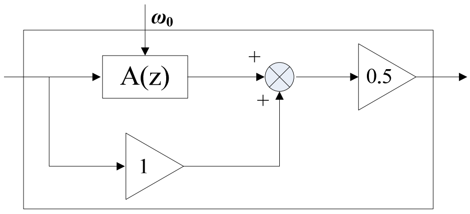


Figure 2. Block Diagram of Notch Filter

Figure 2 shows that the notch filter is consisted of a 2-order Gray-Markel lattice all-pass filter and an adder. The transfer function H(z) is:

$$H(z) = \frac{1 + A(z)}{2} \tag{8}$$

In Equation (8), A(z) is the transfer function of 2-order all-pass filter.

$$A(z) = \frac{k_1 + k_2(1+k_1)z^{-1} + z^{-2}}{1 + k_2(1+k_1)z^{-1} + k_1 z^{-2}} \tag{9}$$

Block diagram of transfer function A(z) is shown in Figure 3. In Equation (9), k_1 controls the bandwidth coefficient of notch filter BW which is related to the distance between the pole and the unit circle. Considering its stability, k_1 usually takes a constant. k_2 is related to ω_0.□ ω_0 is the notch frequency which is the frequency filtered out by notch filter.

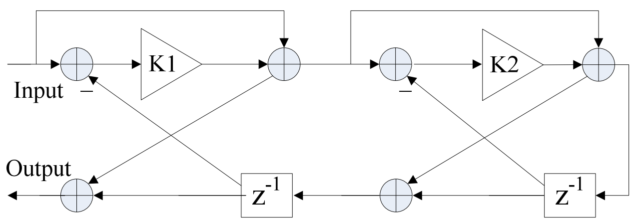


Figure 3. Block Diagram of Transfer Function A(z)

As designing the notch filter, the parameters k_1 and k_2 should be designed independently in order to facilitate the separate control of the notch frequency ω_0 and the -3dB attenuation bandwidth [17]. It is shown in Equation (10).

$$\begin{cases} k_1 = \dfrac{1-\tan\left(BW/2\right)}{1+\tan\left(BW/2\right)} \\ k_2 = -\cos\omega_0 \end{cases} \tag{10}$$

According to Equation (8) and (9), H (z) can be expressed as:

$$H(z) = \frac{1+k_1}{2}\frac{1+2k_2z^{-1}+z^{-2}}{1+\left(k_2+k_1k_2\right)z^{-1}+k_1z^{-2}} \tag{11}$$

In order to facilitate the programming, we define $k_1 = R^2, k_2 = -\cos\omega_0$, so that the notch filter can be designed as Equation (12).

$$H(z) = \frac{1+R^2}{2}\frac{1-2\cos\omega_0 z^{-1}+z^{-2}}{1-\left(1+R^2\right)R\cos\omega_0 z^{-1}+R^2z^{-2}} \tag{12}$$

In Equation (12), ω_0 is the notch frequency, R^2 is the adjustable parameter of the notch frequency. In order to satisfy the stability condition of the notch filter, we should make $|k_1|<1$, that is $R^2<1$. Block diagram of leading angle flux weakening control based on notch filter is shown in Figure 4.

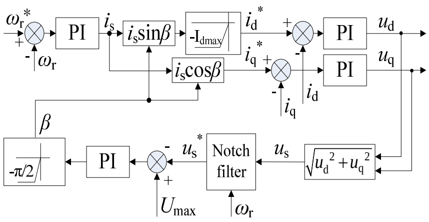


Figure 4. Block Diagram of Leading Angle Flux Weakening Control Based on Notch Filter

As shown in Figure 4, a notch filter is added before the input of PI regulator in flux weakening voltage close-loop to filter the sixth harmonic of input voltage signal u_s caused by SVPWM over modulation, meanwhile the other signal components are not affected. The notch filter is designed according to Equation (12). The value of parameter k_1 is obtained with experience, and it can be adjusted according to the actual situation. Parameter k_2 is the notch frequency which is the sixth harmonic frequency. We can get $\omega_0 = 6\times\omega_r$, and ω_r is the electric angular velocity of PMSM.

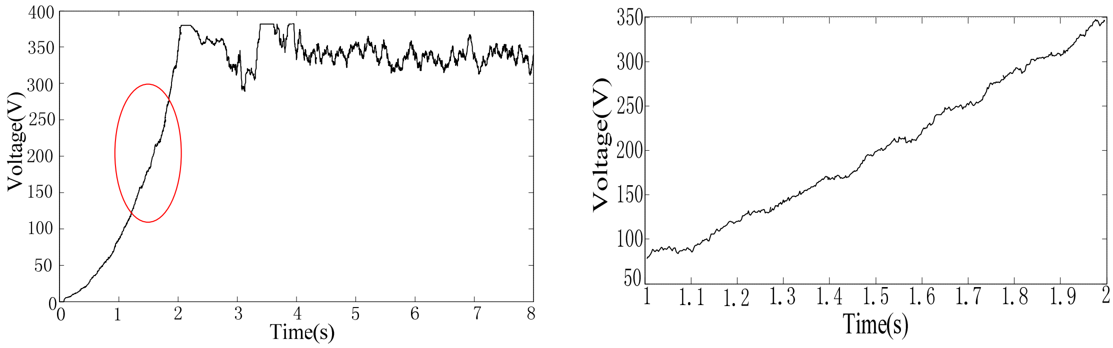
5. Experiment Result

In order to verify the validity of the control method mentioned above, the digital PMSM drive system experimental platform was designed based on the digital signal processor (DSP) in this paper. DSP was TMS320LF2812 of TI, inverter was PM75RSA120 of MITSUBISHI, PMSM was HSB1500908 of INVT, the parameters of the PMSM are shown in Table 1 as follows:

Table 1. Parameter Table of the PMSM

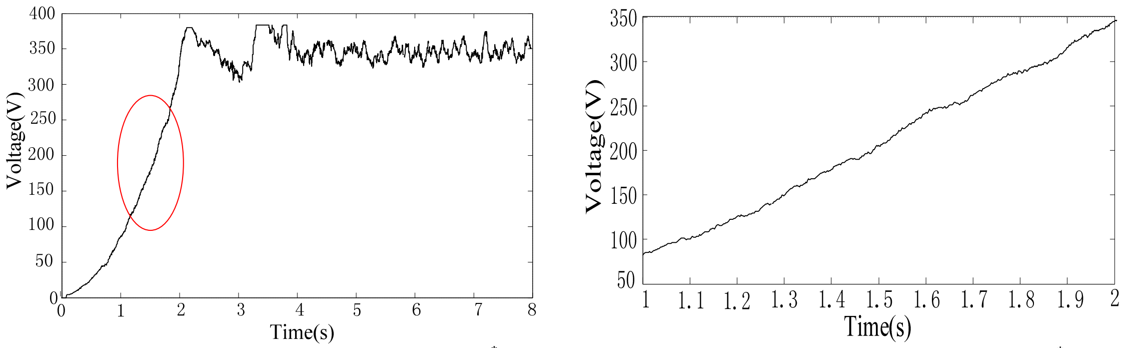
Parameter	Value
rated voltage	310V
rated current	14A
rated power	7.5kW
rated speed	9000rpm
maximum speed	18000rpm
rated torque	8N·m
number of poles	2
rotor inertia	19.5×10^{-4}kg·m^2
rated voltage	310V

Load torque was T_L=4N·m. When the steady-state speed was 16000rpm, the PMSM was into the deep flux weakening region and the inverter was always in the over modulation state. Since the inverter output capacity was limited, the sixth harmonic component in the actual voltage signal u_d and u_q was the main component of harmonic components. The experiment was done with the flux weakening control algorithm based on notch filter proposed in this paper. The experimental results of the input voltage signal u_s and output voltage signal u_s^* is shown in Figure 5 and Figure 6. From the comparison of the two graphs, it is shown that, because of notch filter filtering out the sixth harmonic, the harmonic component of u_s^* is significantly reduced in Figure 6 compared with that of u_s in Figure 5, and the voltage waveform is improved significantly.



(a) The waveform of voltage signal u_s (b) The partial enlarged drawing of u_s at 1s~2s

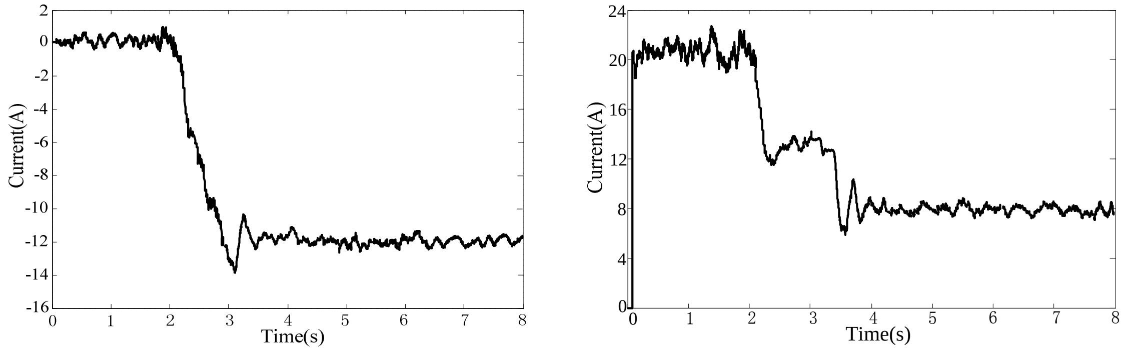
Figure 5. The Waveform of Voltage Signal u_s before Notch Filter



(a) The waveform of voltage signal u_s^* (b) The partial enlarged drawing of u_s^* at 1s~2s

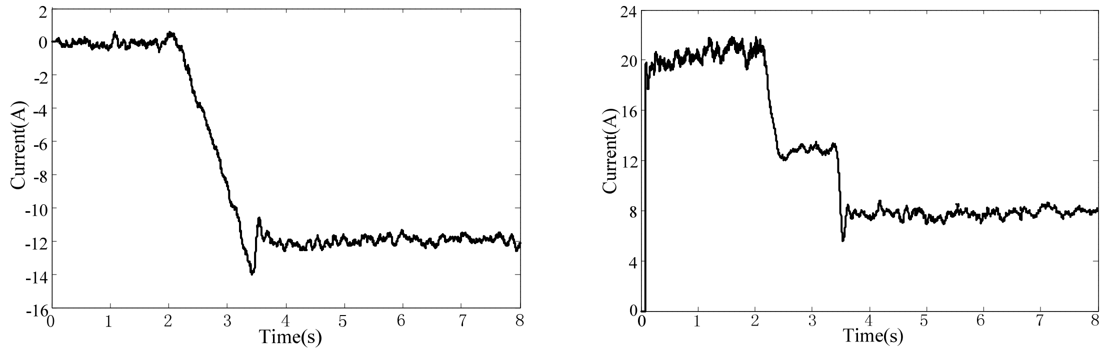
Figure 6. The Waveform of Voltage Signal u_s^* after Notch Filter

The flux weakening control experiment without notch filter was also done to make a comparison. Figure 7 and Figure 8 show the waveforms of d-q currents at steady stage with and without notch filter. In Figure 7, due to the sixth harmonic component from the flux weakening voltage close-loop, there are d-q currents oscillation. After adding the notch filter, as the sixth harmonic component is filtered out by the notch filter, d-q currents oscillation is smaller in Figure 8, so that the current waveform is improved significantly.



(a) The waveform of d-axis current (b) The waveform of q-axis current

Figure 7. The Waveforms of d-q Currents without Notch Filter in the Flux Weakening Region



(a) The waveform of d-axis current (b) The waveform of q-axis current

Figure 8. The Waveforms of d-q and Currents with Notch Filter in the Flux Weakening Region

Figure 9 and Figure 10 show the waveforms of speed at steady stage with and without notch filter in the flux weakening voltage close-loop. As shown in Figure 9, due to the influence of sixth harmonic component on the performance of current loop, there are speed oscillation at steady stage, and the speed performance in flux weakening region becomes worse. After adding the notch filter in Figure 10, as the sixth harmonic of d-q currents is filtered out, the speed oscillation at steady stage is smaller and the speed performance in flux weakening region is obviously improved.

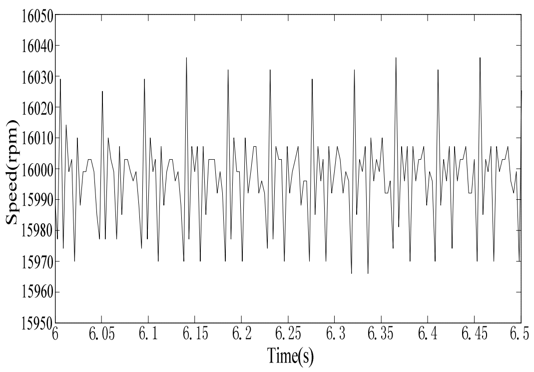


Figure 9. The Waveform of Steady State Speed without Notch Filter in the Flux Weakening Region

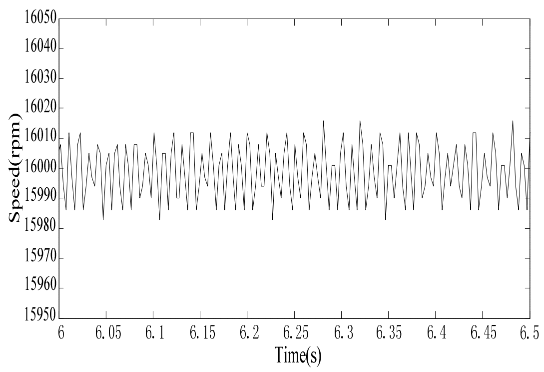


Figure 10. The Waveform of Steady State Speed with Notch Filter in the Flux Weakening region

6. Conclusion

To solve the problem that the sixth harmonic of inverter output voltage caused by SVPWM over modulation which is transmitted to the d-q reference currents through the flux weakening voltage close-loop deteriorate the current and speed control performance of surface-mounted PMSM, a flux weakening control algorithm is proposed. A notch filter is designed in the voltage close-loop to filter the sixth harmonic component of the input voltage signal, meanwhile the other signal components are not affected. Experiment results show that, the sixth harmonic component of the input voltage signal is significantly reduced and the fluctuation of speed decreases, so that the steady performance of flux weakening control is effectively improved and the robustness of system is remarkably enhanced.

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