論 文
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약계자 영역에서 전동기 상수변동에 둔감한 SPMSM의 새로운 약계자 제어기

A New Robust SPMSM Control to Parameter Variations in Flux Weakening Region

金長睦*, 宋鐘煥**, 薛承基***
(Jang-Mok Kim, Jong-Hwan Song, Seung-Ki Sul)

Abstract – A new implementation strategy for the flux weakening control of a Surface Mounted Permanent Magnet Synchronous Motor (SPMSM) is proposed. It is implemented based on the output of the synchronous PI current regulator - reference voltage to PWM inverter. The onset of flux weakening and the level of the d-axis current are adjusted by the outer voltage regulation loop to prevent the saturation of the current regulator. The characteristics of this flux weakening scheme include no dependency on the machine parameters, the guarantee of current regulation on any operating condition, and fast transition into and out of the flux weakening mode. Experimental results at various operating conditions including 4-quadrant operation are presented to verify the feasibility of the proposed control scheme.

Key Words : Flux weakening, SPMSM, Outer voltage regulation loop

1. Introduction

Recently, the high performance motor drive system has gained the increasing popularity in industrial applications. At such system, fast response to the reference change, robustness to the load variation and minimizing the speed and torque ripple are essential. Moreover to increase the productivity it is inevitable to extend the speed range. To extend the speed range, flux weakening scheme is generally used[1-5,8]. Permanent-magnet synchronous machine drives possess many attractive features such as good efficiency, high power rate, robustness, and linear torque characteristic. However, as the speed increases, the back EMF also increases by which the current control is rendered ineffective and eventually the generating torque is degraded[5].

To extend the speed range, there were many researches on Interior Permanent Magnet Motor(IPM) which has the rotor saliency, the small effective airgap and the robust rotor shape. So it is possible to operate at high speed operation[1-3]. By the way, the possibility of the flux weakening operation of Surface Mounted Permanent Magnet Synchronous Motor(SPMSM) have been presented theoretically[4,5] and also the control methods of the flux weakening are presented[6,7]. One method of d-axis current control is to calculate the d-axis current reference directly from (9)[6]. But this method is so sensitive to motor parameters. The other method is to determine the d-axis current reference which is proportional to the q-axis current error[7]. If there is a large q-axis current error, then negative d-axis current is injected and the marginal voltage is ensured to control the q-axis current. However this strategy has instability in itself and the current response is deteriorated because the filter should be used to smooth the stator current ripple.

In this paper, a new method of flux weakening control which guarantees the stable operation of both the transient state and steady state is presented. For stable operation, this scheme uses the outer voltage regulation loop by which the references of d- and q-axis current are calculated and supplied to the current controller to prevent the saturation of current controller. This scheme does not require the machine parameters and additional hardware. The effectiveness of the proposed scheme is verified experimentally.

2. State Equations of PMSM

In the synchronous reference frame, the voltage equations of the surface mounted PM motor are as follows,

$$V_{qs}^{e} = R_s i_{qs}^{e} + L_s \frac{i_{qs}^{e}}{dt} + \omega_e L_s i_{ds}^{e} + \lambda_m \omega_e . \quad (1)$$

$$V_{ds}^{e} = R_s i_{ds}^{e} + L_s \frac{i_{ds}^{e}}{dt} - \omega_e L_s i_{qs}^{e} . \quad (2)$$

where, R_s, L_s : stator resistance and inductance.
V_{qs}^{e}, V_{ds}^{e} : q-d axis voltage component

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*正 會 員 : 韓電 電力硏究院 先任硏究員 · 工博
**正 會 員 : 曉星重工業(株) · 工博
***正 會 員 : 서울大 工大 電氣工學部 副敎授 · 工博

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i_{qs}^e, i_{ds}^e : q-d axis current component

ω_e : rotor speed in electrical angle

λ_m : flux linkage of permanent magnet.

Superscript 'e' denotes a quantity that is expressed in the synchronously rotating reference frame and subscript 's' denotes a stator element. At the low speed, the electromotive force term of (1) is so that there exists enough voltage margin for current control. However as the rotor speed increases, the marginal voltage to control the current is decreased and hence the torque becomes highly distorted. So it is no more possible to extend the speed range else if the flux weakening method should be applied. (1) shows that the rotor speed,, can be extended by injecting the d-axis current, i_{ds}^e , negatively. But the extension range of the speed is limited by the structures and the parameters of the motors under the given conditions of voltage and current limitation[5].

3. Description of Flux Weakening Control Scheme

3. 1 Operating limits in flux-weakening region

The maximum voltage that the inverter can supply to the machine is limited by DC link voltage and PWM strategy. In this paper, a PWM strategy based on voltage space vector is used and then can be identified as $V_{dc}/\sqrt{3}$. Also the maximum current $I_{s.\max}$ is determined by the inverter current rating and machine thermal rating. Therefore the voltage and current of the motor have the following limits:

$$V_{ds}^{e\,2} + V_{qs}^{e\,2} \le V_{s.\max}^{\;2}. \qquad (3)$$

$$i_{ds}^{e\,2} + i_{qs}^{e\,2} \le I_{s.\max}^{\;2} \qquad (4)$$

As the speed increases above the rating speed the term of is so large that the effect of resistance voltage drop can be neglected, and the steady state voltage equation can be written of (1), (2) as follows,

$$V_{qs}^e = \omega_e L_s i_{ds}^e + \lambda_m \omega_e \qquad (5)$$

$$V_{ds}^e = -\omega_e L_s i_{qs}^e \qquad (6)$$

From (3) to (6), can be eliminated and can be expressed as follows,

$$\left(i_{ds}^e + \frac{\lambda_m}{L_s}\right)^2 + (i_{qs}^e)^2 \le \left(\frac{V_{s.\max}}{\omega_e L_s}\right)^2. \qquad (7)$$

This equation expresses the limit circle of which the radius is $\frac{V_{s.\max}}{\omega_e L_s}$ and the center is $\left(-\frac{\lambda_m}{L_s}, 0\right)$ as 'voltage limit' in Fig. 1. This figure shows that the voltage limit circle is decreased as the rotor speed increases, but the current limit circle is constant irrespective of the speed. The maximum torque point is on the cross point of current and voltage limit circles. As a result the operating point moves from A to B as speed increases and arrives at C at the steady state. And the maximum torque value is the function of speed as follows,

$$\begin{aligned} T_e &= \frac{3}{2}\frac{P}{2}\lambda_m i_{qs}^e \\ &= \frac{3}{2}\frac{P}{2}\lambda_m \sqrt{\left(\frac{V_{s.\max}}{\omega_e L_s}\right)^2 - \frac{1}{4}\left(\frac{\lambda_m}{L_s}\right)\left(1+\left(\frac{V_{s.\max}}{\omega_e \lambda_m}\right)^2 - \left(\frac{L_s}{\lambda_m} I_{s.\max}\right)^2\right)^2}. \end{aligned} \qquad (8)$$

Also the d-axis current $i_{ds}^{e\,*}$ for flux weakening operation is the function of speed as follows,

$$i_{ds}^{e\,*} = \frac{1}{2}\frac{L_s}{\lambda_m}\left(\left(\frac{V_{s.\max}}{\omega_e}\right)^2 - \left(\frac{\lambda_m}{L_s}\right)^2 - I_{s.\max}^2\right) \qquad (9)$$

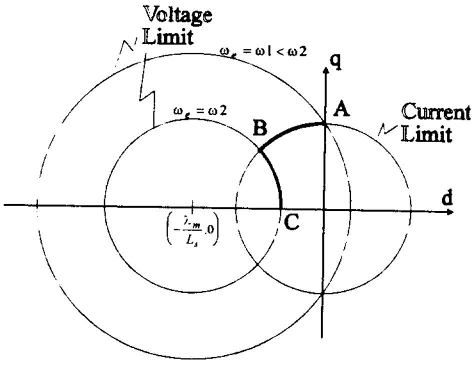

Fig. 1. Space vector diagram for maximum torque in a SPMSM

3. 2 Description and Features of the proposed flux weakening scheme

The flux weakening control of PMSM is conducted by increasing the d-axis current, i_{ds}^e , negatively which is different from induction machine where the flux is weakened by decreasing the d-axis current[8]. This inevitably decreases the q-axis current, i_{qs}^e , which is proportional to producing torque, hence the d-axis current should be as small as possible to maximize the producing torque.

In the proposed method, the main idea is the use of the output reference voltage of the synchronous PI current regulator to identify the onset of the flux weakening as depicted in Fig.2 by hatched area. So the onset point of flux weakening is detected and the flux level is adjusted autonomously by this outer voltage regulator. And the system is independent of motor parameters such as resistance,

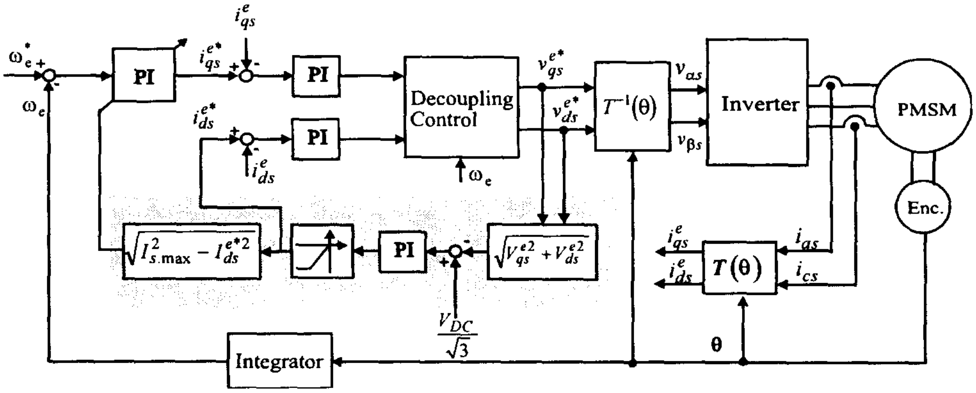

Fig. 2. The block diagram of PMSM drive system including the proposed flux weakening scheme.

inductance, and flux linkage. Fig. 2 illustrates a block diagram of the speed control system including the proposed flux weakening control algorithm. In the flux-weakening region, if the voltage vector exceeds the maximum voltage limit circle, $V_{s.\max} = (V_{dc}/\sqrt{3})$, then the controller senses the error of the voltage and injects the d-axis current negatively to prevent the saturation of the current regulator. With thanks to this outer voltage regulation loop the flux weakening is accomplished automatically. At low and intermediate speed region, the magnitude of the output voltage of the current regulator $V_{qds}^{e\ *} = (\sqrt{V_{ds}^{e\ *2} + V_{qs}^{e\ *2}})$ is usually less than $V_{s.\max}$ and thus the flux -weakening algorithm is not activated. Even if the dc link voltage drops suddenly, the flux weakening operation can be carried out autonomously because the voltage feedback can adjust the flux level autonomously. The d-axis current reference, $i_{ds}^{e\ *}$, calculated by the proposed method is the input to the synchronous PI current controller to generate the d-axis voltage reference, $v_{ds}^{e\ *}$, and the total current $I_{qds}^{e\ *} = (\sqrt{I_{ds}^{e\ *2} + I_{qs}^{e\ *2}})$ can not be exceeded the current limit value, $I_{s.\max}$, so the limit of q-axis current reference is calculated and used at the speed controller as a limit value.

4. Experimental Results

4. 1 Hardware Configuration

The overall experimental system configuration is shown in Fig.3. The power circuits are composed of IGBT power module. The sampling period of current controller is 150 μsec and that of the speed controller and the proposed outer voltage regulation loop 1.5 $m$sec. In this system the dc link voltage is set as 150 V, the effective dc link voltage is less than 140 V since the dead time of the inverter is 3.5 μsec and voltage drop of switching device. As a main processor, TMS320C31 DSP is used in this system which operates at 33.33Mhz clock and is capable of 32-bit floating point operation. The actual current and dc link voltage are detected by sensors and processed by 12-bit A/D converter. All internal data of DSP can be displayed through a 4-channel 12-bit D/A converter.

4. 2 Experimental Results

The ratings and parameters of SPMSM are shown at Table 1. The bandwidth of the proposed system is 3000[rad/s] for the current controller and 250[rad/sec] for the speed controller respectively. The speed command is alternating between -2400rpm and 2400rpm. The dynamics

Table 1. The ratings and parameters of SPMSM

Ratings	800[W], 220[V], 8 poles, 2000 [rpm]
Moment of Inertia	J_m = 0.0244 [$Kg \cdot m^2$]
Stator Resistance	R_s = 1.5 [Ω]
Stator Inductance	L_s = 3.3 [mH]
Flux Linkage	λ_m = 0.09 [wb]

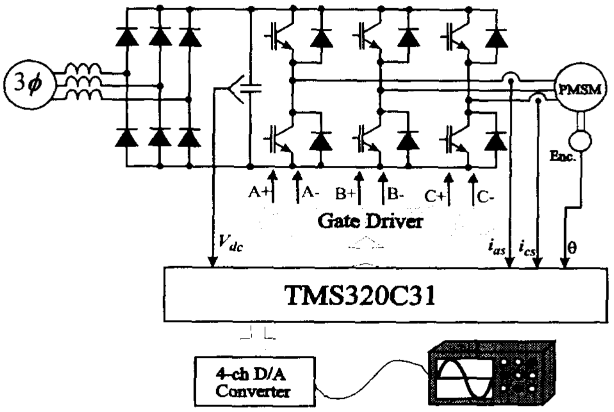

Fig. 3. Overall experimental system configuration

of the motor operation of conventional and proposed schemes are indicated in Fig.4 - 8. Each figure shows the transient responses of the speed reference, the motor speed, the q-axis current, and the d-axis current.

Fig.4 shows the responses of speed control without non-flux weakening control. This figure shows that above the rated speed, the torque is abruptly decreasing and also the maximum speed is no more than 2100[rpm].

The responses of conventional field weakening method are shown at Fig.5 and Fig.6 when the d-axis current reference is directly calculated using the electrical model of SPMSM[6]. Fig.5 shows the transient responses when the motor parameters are exactly tuned and Fig. 6 shows the results when the ambient temperature is increasing from 25 °C to 75 °C.

The other conventional method where the d-axis current reference is proportional to the q-axis current error[7] is shown at Fig. 7. The time constant of filter is set to 75[msec]. At steady state this figure shows a high current ripple from the current controller. If the time constant of filter is increased, then the response is deteriorated.

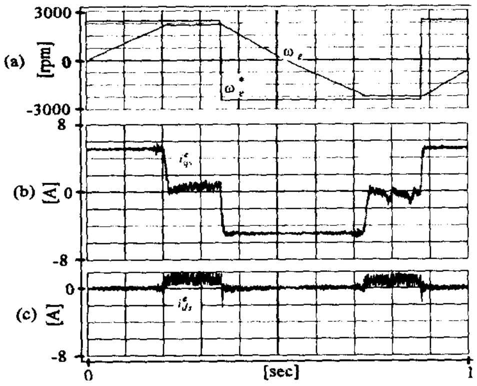

Fig. 4. Experimental results without flux weakening control.
(a) Speed reference and real rotor speed
(b) q-axis real current (c) d-axis real current

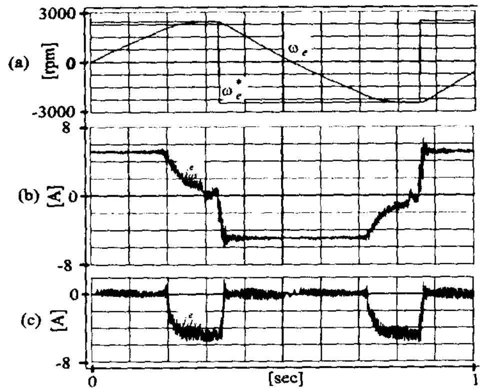

Fig. 5. Experimental results of conventional scheme[6] when exactly tuned.
(a) Speed reference and real rotor speed
(b) q-axis real current (c) d-axis real current

The transient response of the proposed strategy is shown in Fig. 8. In the proposed flux weakening scheme the machine parameters is used to compensate the cross coupling effect in the synchronous d-q current regulator.

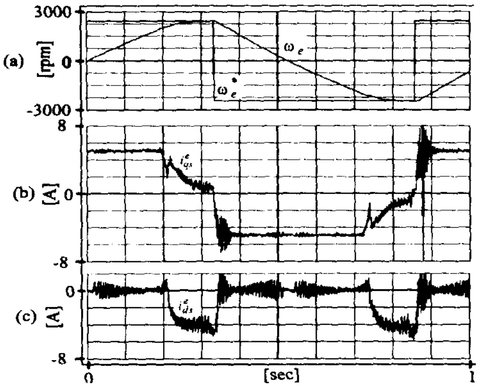

Fig. 6. Experimental results of conventional scheme[6] when detuned.
(a) Speed reference and real rotor speed
(b) q-axis real current (c) d-axis real current

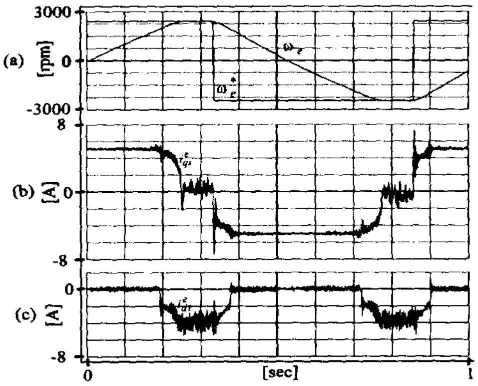

Fig. 7. Experimental results of conventional scheme[7].
(a) Speed reference and real rotor speed
(b) q-axis real current (c) d-axis real current

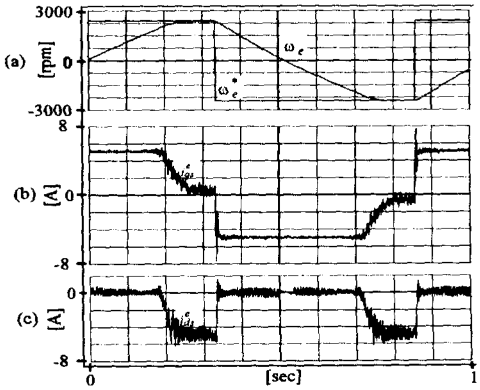

Fig. 8. Experimental results of proposed scheme.
(a) Speed reference and real rotor speed
(b) q-axis real current (c) d-axis real current

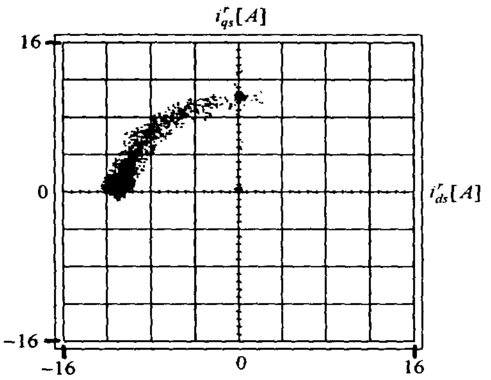

Fig. 9. Current trajectory in the $i^e_{qs}-i^e_{ds}$ plane.

The q- and d-axis currents can not be controlled independently by V^e_{qs}, V^e_{ds} because of the cross-coupling effect such as $\omega_e L_s i^e_{qs}$, $\omega_e(L_s i^e_{ds}+\lambda_m)$. The effect increases as speed increases. So the current response as well as torque response are affected by this effect in the high speed region. But the cross-coupling effect can be compensated by the back EMF $\omega_e L_s i^e_{qs}$, $\omega_e(L_s i^e_{ds}+\lambda_m)$. The steady state and the dynamic performance can be improved by using the feed forward de-coupling control not only in the constant torque region but also in the flux weakening even though the values of the motor parameters are severly detuned. Therefore the proposed flux weakening scheme is not affected by the detuned machine parameters as shown from the experimental results, Fig.8. From this fact the proposed flux weakening method has the better response than the conventional methods. These experimental results verify the effectiveness of the proposed flux weakening method.

Fig.9 is the current trajectory of $i^e_{qs}-i^e_{ds}$ for maximum torque operation in the flux weakening region. It was already explained in Fig. 1.

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저자소개

김 장 목 (金 長 睦)

1961년 8월 6일생. 1998년 부산대 공대 전기공학과 졸업. 1988년 한국전력공사 근무. 1991년 서울대 대학원 전기공학과 졸업(석사). 1996년 서울대 전기공학부 졸업(공박). 현재 한국전력 전력연구원 발전연구실 선임연구원.

Tel : (042) 865-5266
E-mail : kjm@kepri.re.kr

송 종 환 (宋 鍾 煥)

1958년 7월 17일생. 1982년 서울대 공대 전기공학과 졸업. 1984년 동 대학원 전기공학과 졸업(석사). 1996년 동 대학원 전기공학부 졸업(공박). 1994년~현재 효성중공업(주) 근무.

Tel : (02) 3487-0001 (교) 145
E-mail : songjw@rico.hyosung.co.kr

설 승 기 (薛 承 基)

1958년 3월 25일생. 1980년 서울대 공대 전기공학과 졸업. 1986년 동 대학원 전기공학과 졸업(공박). 1986년~1988년 미국 Univ. of Wisconsin-Madison 객원 연구원. 1988년~1990년 금성산전연구소 책임연구원. 현재 서울대 공대 전기공학부 부교수.