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A flux estimation method for a permanent-magnet synchronous motor

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Abstract

This paper deals with the flux estimation of a permanent-magnet synchronous motor (PMSM). Contrary to the conventional no-load test, the proposed method needs no extra servomotor. It is simply to drive the PMSM in a single-phase mode with the currents large enough to make the PMSM rotate in the same direction. Under such a condition, the flux of the PMSM can be easily estimated.

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Keywords: PMSM; No-load test; Emf; Flux estimation

1. Introduction

The permanent-magnet synchronous motor (PMSM) has been used broadly in industry, because of its easy controllability and fast response. An accurate estimation of the flux is useful for the design and the servo control of a PMSM. Several researches have dealt with the estimation of the flux of a PMSM [1–3]. It is of no doubt that the no-load test method [1] has become the most popular one. In this method, an auxiliary motor is required to drive the PMSM at constant speed. The windings of PMSM are at open-circuit so that the flux can be estimated by the emf of the PMSM.

This paper tries to propose an alternative estimation method, which does not require the aid of an auxiliary servomotor. The proposed method is simply to drive the PMSM by exciting a single phase, say, let $i_a = -i_b$, and $i_c = 0$, where i_a, i_b, and i_c are the currents of phases a, b, c, respectively. The flux is then easily estimated using the measurement of three terminal voltages v_a, v_b, and v_c.

A spindle motor in a 50×XCD-ROM driver is taken as an example to compare the estimation results between the proposed method and the conventional no-load test. It will be shown that the experiment results of both methods are very close.

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2. Proposed method

Consider a PMSM with three-phase and Y-connected windings, whose models can be described as [4]

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s & -M & -M \\ -M & L_s & -M \\ -M & -M & L_s \end{bmatrix} \begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} + \omega_r \lambda_r \begin{bmatrix} \cos\theta_r \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) \end{bmatrix}, \quad (1)$$

where v_{as}, v_{bs}, and v_{cs}, are the terminal voltages with respect to the neutral point s (see Fig. 1(a)), i_a, i_b, and i_c are the currents of phases a, b, c, respectively, r_s is the winding resistance per phase, L_s is the self-inductance per phase, M is the mutual inductance per phase, ω_r is the electric angular speed of the rotor, λ_r is the maximum flux induced by the rotor magnet, and θ_r is the rotational electrical angle of the rotor. Note that $\theta_r = 0$ is the position where the intersection line of the N–S and the S–N magnet is in alignment with the centerline of a tooth of phase a (see Fig. 1(b)). Furthermore, the output torque T_e of the motor can be obtained as

$$T_e = \frac{P}{2}\lambda_r\left(\left(i_a - \frac{i_b}{2} - \frac{i_c}{2}\right)\cos\theta_r + \frac{\sqrt{3}}{2}(i_b - i_c)\sin\theta_r\right) = \frac{2J}{P}\frac{d\omega_r}{dt} + \frac{2B_m}{P}\omega_r + T_L, \quad (2)$$

where J is the inertia, P is the number of poles of the magnet, B_m is the damping ratio, and T_L is the loading torque. Suppose that the PMSM is operated in a single-phase mode, i.e., phase c is open, such that $i_a = -i_b$, and $i_c = 0$. Such a kind of operation can be achieved by manipulating four transistors on legs, Leg_2 and Leg_3, in Fig. 1(a), while turning those on Leg_1 always open. Under this situation, Eq. (1) is simplified in the form of

$$\begin{aligned} v_{as} &= v_a - v_s = r_s i + L_s\frac{di}{dt} + M\frac{di}{dt} + \omega_r\lambda_r\cos\theta_r, \\ v_{bs} &= v_b - v_s = -r_s i - L_s\frac{di}{dt} - M\frac{di}{dt} + \omega_r\lambda_r\cos\left(\theta_r - \frac{2\pi}{3}\right), \\ v_{cs} &= v_c - v_s = \omega_r\lambda_r\cos\left(\theta_r + \frac{2\pi}{3}\right), \end{aligned} \quad (3)$$

where v_a, v_b, and v_c are the terminal voltages, and v_s is the neutral voltage. Similarly, Eq. (2) is also simplified as

$$T_e = \frac{\sqrt{3}P}{2}\lambda_r i(t)\cos\left(\theta_r + \frac{\pi}{6}\right) = \frac{2J}{P}\frac{d\omega_r}{dt} + \frac{2B_m}{P}\omega_r + T_L. \quad (4)$$

According to Eq. (4), we can make the motor rotate continuously in one direction by simply

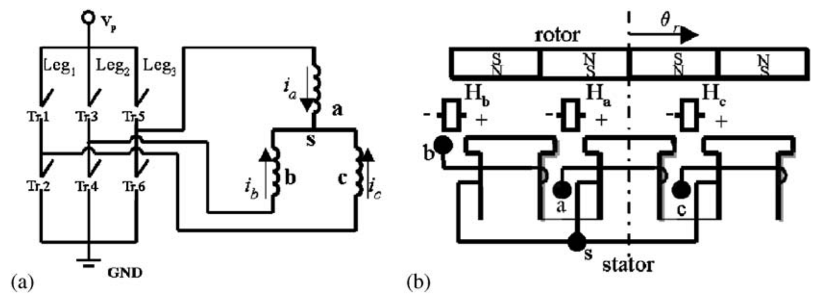

Fig. 1. (a) A three-phase PMSM with Y-connected windings and its driver. (b) The relative position between the stator and the rotor at $\theta_r = 0$.

assigning the current $i(t)$ in phase with $\cos(\theta_r+\pi/6)$, and large enough to ensure $T_e > T_L$. Since the values of v_{as}, v_{bs}, and v_{cs} are not available and only v_a, v_b, and v_c can be measured, we introduce a new variable $v_\omega(t)$ defined as

$$v_\omega(t) \equiv \frac{-(v_a + v_b - 2v_c)}{3} = \omega_r\lambda_r \cos\left(\theta_r + \frac{2\pi}{3}\right). \tag{5}$$

It follows from Eq. (5) and $\omega_r = d\theta_r/dt$ that

$$v_\omega(t)dt = \lambda_r \cos\left(\theta_r + \frac{2\pi}{3}\right)d\theta_r. \tag{6}$$

Integrating both sides of Eq. (6) leads to

$$\begin{aligned}\Psi(t) &\equiv \int_0^t v_\omega(\tau)d\tau = \int_{\theta_r(0)}^{\theta_r(t)} \lambda_r \cos\left(\tau + \frac{2\pi}{3}\right)d\tau \\ &= \lambda_r \sin\left(\theta_r(t) + \frac{2\pi}{3}\right) - \lambda_r \sin\left(\theta_r(0) + \frac{2\pi}{3}\right) \\ &= \lambda_r \sin\left(\theta_r(t) + \frac{2\pi}{3}\right) + \Psi_0 \end{aligned} \tag{7}$$

where Ψ_0 is a constant. Consequently, the flux estimation method is that the PMSM is operated in a single-phase mode with the current in phase with $\cos(\theta_r+\pi/6)$ and large enough to overcome the load T_L, and the measured histograms of v_a, v_b, and v_c are used to calculate $v_\omega(t)$ in Eq. (5) and then $\Psi(t) = \int_0^t v_\omega(\tau)d\tau$. The flux λ_r of the PMSM is then the amplitude of the sinusoidal part of Ψ(t) according to Eq. (7).

3. Implementation

A three-phase, 12-pole, and nine-slot DC brushless motor used as a spindle motor of a $50\times$XCD-ROM is taken as an example. The motor with $\lambda_r = 7.9\times10^{-4}$ Wb-turn has the surface-mounted NdFeB magnet rotor. There are three Hall elements H_a, H_b, and H_c mounted on the stator (see Fig. 1(b)), each of which generates a pair of differential signals, e.g., H_a^+ and H_a^-, as the feedback signals for the motor driver. Now, we want to establish a driving system that drives the PMSM only in a single-phase mode as described in Section 2. First, the winding labeled c in Fig. 1(a) should be floated from the transistors.

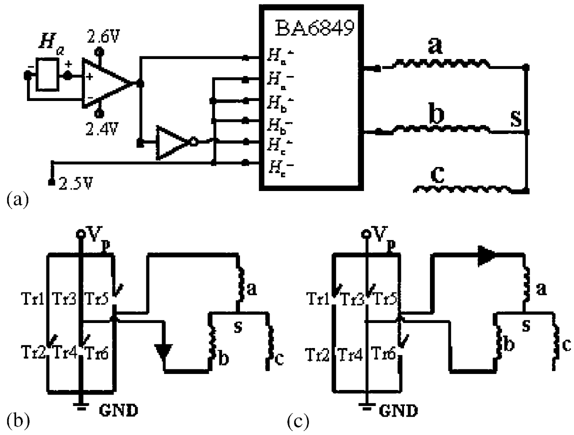

Fig. 2. (a) The modified driven circuits of the Hall elements. (b) The PMSM is operated by state 1. (c) The PMSM is operated by state 4.

When transistors Tr4 and Tr5 in Fig. 1(a) are on and Tr3 and Tr6 are off, the currents of the PMSM are $i_a = -i_b$, and $i_c = 0$ as shown in Fig. 2(c). On the other hand, the currents are reversed when Tr3 and Tr6 are on and Tr4 and Tr5 are off as shown in Fig. 2 (b). Both cases of the single-phase mode can be implemented with a BA6849 chip of the Rohm Company.

The logic table of the BA6849 is shown in Table 1. It is apparent that the states 1 and 4 meet the requirements of the circuits of Fig. 2(b) and (c), respectively. In these two states, the inputs H_a^-, H_b^+, H_b^-, and H_c^- should be retained at the level of $M = 2.5$ V, while those of H_a^+ and H_c^+ are in opposite levels, i.e., $H_c^+ = L$, when $H_a^+ = H$. The implementation circuit is then connected to the input pins H_a^-, H_b^+, H_b^-, and H_c^- to a power source of the voltage level 2.5 V, and to pass the signal of H_a^+ also to pin H_c^+ via a NOT device (see Fig. 2(a)). The output signals of the Hall sensor H_a are operated by a comparator to generate the signal for the input pin H_a^+ of the BA6849. If the positive end of the sensor H_a has a higher voltage level than the negative end, the output of the comparator is 2.6 V. If the positive end has a lower voltage level, then the output of the comparator is 2.4 V. The rotor flux linkage measured by the Hall sensor H_a is so arranged to be proportional

Table 1
The logic table of BA6849

N	Tr1	Tr2	Tr3	Tr4	Tr5	Tr6
Output table						
1	On	Off	On	Off	Off	On
2	On	Off	Off	On	Off	On
3	On	Off	Off	On	On	Off
4	Off	On	Off	On	On	Off
5	Off	On	On	Off	On	Off
6	Off	On	On	Off	Off	On
N	H_a^+	H_a^-	H_b^+	H_b^-	H_c^+	H_c^+
Input table						
1	H	M	M	M	L	M
2	M	M	H	M	L	M
3	L	M	H	M	M	M
4	L	M	M	M	H	M
5	M	M	L	M	H	M
6	H	M	L	M	M	M

$H = 2.6\,\text{V}$, $M = 2.5\,\text{V}$, $L = 2.4\,\text{V}$.

to $\sin(\theta_r + 2\pi/3) = -\cos(\theta_r + \pi/6)$. Thus, the input signal of H_a^+ is in phase of $-\cos(\theta_r + \pi/6)$, so that the current i is in phase of $\cos(\theta_r + \pi/6)$.

An experiment is conducted by the implemented system for the PMSM described above. The current i generated by the BA6849 is measured and shown in Fig. 3(a), while the input signal of pin H_a^+ is shown in Fig. 3(b). It is apparent that the current i is positive when the state of H_a^+ is L, and negative when that of H_a^+ is H. The voltages of v_a, v_b, and v_c are also measured to compute v_ω by Eq. (5) and thus Ψ by Eq. (7), whose results are shown in Fig. 4(a) and (b), respectively.

The constant part of Ψ in Fig. 4(b) is about $\Psi_0 = -7.8 \times 10^{-4}$ Wb-turn, while the amplitude of the sinusoidal part of Ψ is 7.7×10^{-4} Wb-turn. Thus, $\lambda_r = 7.7 \times 10^{-4}$ Wb-turn. The conventional method with no-load test uses a servomotor to drive a PMSM at a constant speed. Since the PMSM is free to run, the three phase currents of the PMSM are all zero, i.e., $i_a = i_b = i_c = 0$. Under such a situation, the emf v_a and v_b of phases a and b are measured to compute $v_{ab} = v_{as} - v_{bs} = v_a - v_b = \sqrt{3}\lambda_r\omega_r \cos(\theta_r + \pi/6)$, which follows from Eq. (1) for $i_a = i_b = i_c = 0$. Because

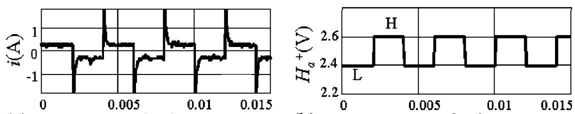

Fig. 3. (a) The $i-t$ plot of a PMSM in the single-phase rotation. (b) The plot of the input signal of pin H_a^+ and time t.

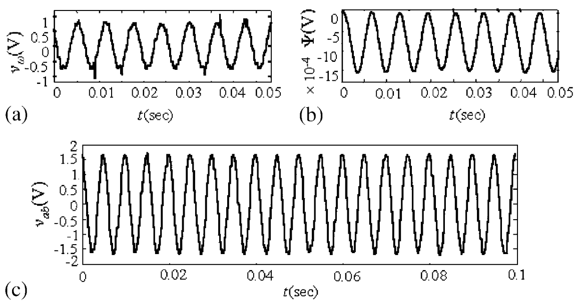

Fig. 4. (a) The plot of $v_\omega - t$. (b) The plot of $\Psi - t$. (c) The line emf v_{ab} of the PMSM driven by an auxiliary motor.

the speed of the PMSM is known, λ_r is then $(1/(\sqrt{3}\omega_r)$ times the amplitude of the sinusoidal v_{ab}. Fig. 4(c) shows the experiment results of the conventional method, which allows us to calculate out $\lambda_r \approx 7.62 \times 10^{-4}$ Wb-turn. This verifies that the proposed method is reliable.

4. Conclusion

This paper proposes a flux estimation method for a PMSM. The PMSM is operated in a single-phase mode and the currents are controlled so that the PMSM rotates in the same direction. Under such a condition, calculating out $\Psi(t)$ in Eq. (7) allows us to obtain the flux λ_r as the amplitude of the sinusoidal part of $\Psi(t)$. An implemented system with a BA6849 chip is established to verify the proposed method.

Acknowledgements

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