Rotor Position and Speed Estimation of PMSM Based on BEMF Method

Guanglin Dong[a], Dafang Wang[b], and Mingyu Wang[c]

School of Automotive Engineering, Harbin Institute of Technology at Weihai, Weihai 264200, China

[a]haweidong@126.com, [b]wdflcjl@163.com, [c]786795253@qq.com

Keywords: PMSM, Rotor Position, Speed Estimation

Abstract: Permanent magnet synchronous motor (PMSM) sensorless control is a research hotspot at present. The position and speed estimation of PMSM rotor based on back electromotive force (BEMF) is widely used in industrial control due to its simple principle and high estimation accuracy at high speed. In this paper, the principle of estimating rotor position and speed based on BEMF is deduced by PMSM mathematical model in two-phase stationary coordinate system, and the closed-loop control system of PMSM is designed based on the estimated rotor position and speed. It is also pointed out that there are some problems in the actual implementation of BEMF method, such as integral zero drift, fluctuation of speed estimation, variation of PMSM parameters and limited application scope, and the solutions are given in the end.

1. Introduction

PMSM has the advantages of small size and high power density and is widely used in industrial control systems. In order to improve the control performance of the PMSM, sensors such as encoder and rotary transformer are often used to obtain the rotor position and speed information. However, the use of position sensors increases the cost of control systems, enlarges the volume of PMSM, and reduces the reliability of the PMSM working in special conditions. In view of this situation, many scholars begin to study the sensorless control strategy of PMSM and a variety of rotor position and speed estimation methods are proposed, including high-frequency injection method [1, 2], phase-locked loop position observer method [3], adaptive sliding mode observer method [4], model reference adaptive method [5] and BEMF estimation method [6]. Among them, a kind of estimation method based on motor BEMF is widely used because of its simple algorithm principle. This paper will deduce and analyze the principle of estimating rotor position and speed based on BEMF.

2. Principle of BEMF Method

BEMF method can obtain accurate and reliable estimation results in the middle and high speed section of PMSM. Combining with close-loop vector control, it has good dynamic performance and is suitable for all kinds of PMSM. The rotor position and speed estimation algorithms based on BEMF can be derived from the mathematical model of PMSM. The flux equation of PMSM in the *d*-*q* coordinate system is

$$\begin{bmatrix}\psi_d \\ \psi_q\end{bmatrix}=\begin{bmatrix}L_\mathrm{d} & 0 \\ 0 & L_q\end{bmatrix}\begin{bmatrix}i_d \\ i_q\end{bmatrix}+\begin{bmatrix}\psi_f \\ 0\end{bmatrix} \tag{1}$$

According to the inverse PARK coordinate transformation, equation (1) can be transformed into the α-β coordinate system as:

$$\begin{bmatrix}\psi_\alpha \\ \psi_\beta\end{bmatrix}=\begin{bmatrix}L_1+L_2\cos 2\theta_e & L_2\sin 2\theta_e \\ L_2\sin 2\theta_e & L_1-L_2\cos 2\theta_e\end{bmatrix}\begin{bmatrix}i_\alpha \\ i_\beta\end{bmatrix}+\psi_f\begin{bmatrix}\cos\theta_e \\ \sin\theta_e\end{bmatrix} \tag{2}$$

The voltage equation of the PMSM in the coordinate system is given as follows:

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + p \begin{bmatrix} \psi_\alpha \\ \psi_\beta \end{bmatrix} \tag{3}$$

In the above formula, ψ_{dq}, $\psi_{\alpha\beta}$, i_{dq}, and $i_{\alpha\beta}$ are the stator flux and current of the PMSM in different coordinate systems, L_d and L_q are the d axis and q axis inductance of the PMSM, ψ_f is the rotor permanent magnet flux, θ_e is the electrical angle of the rotor, and common-mode inductance L_1 and differential-mode inductance L_2 are defined as $L_1 = \frac{L_d+L_q}{2}$, $L_2 = \frac{L_d-L_q}{2}$. In addition, $u_{\alpha\beta}$ is defined as the α and β phase voltage of the PMSM, R_s is the stator resistance and p is the differential operator.

For surface mounted PMSM, there is $L_d = L_q$, so $L_2 = 0$. Equation (3) can be written in the following form:

$$\begin{aligned} u_\alpha &= Ri_\alpha + p(L_1 i_\alpha + \psi_f \cos\theta) \\ u_\beta &= Ri_\beta + p(L_1 i_\beta + \psi_f \sin\theta) \end{aligned} \tag{4}$$

The PMSM stator flux linkage can be obtained by integrating equation (4) as

$$\begin{aligned} \psi_\alpha &= \int (u_\alpha - Ri_\alpha) dt \\ \psi_\beta &= \int (u_\beta - Ri_\beta) dt \end{aligned} \tag{5}$$

Thus, the estimated rotor position and speed can be expressed as

$$\theta_e = \tan^{-1} \frac{\psi_\beta - L_1 i_\beta}{\psi_\alpha - L_1 i_\alpha} \tag{6}$$

$$\omega_r = \frac{1}{n_p} \frac{d\theta_e}{dt} \tag{7}$$

In equation (7), ω_r is rotor mechanical angular velocity and n_p is pole pairs.

The principle of PMSM closed-loop sensorless control based on the above BEMF method is shown in figure 1.

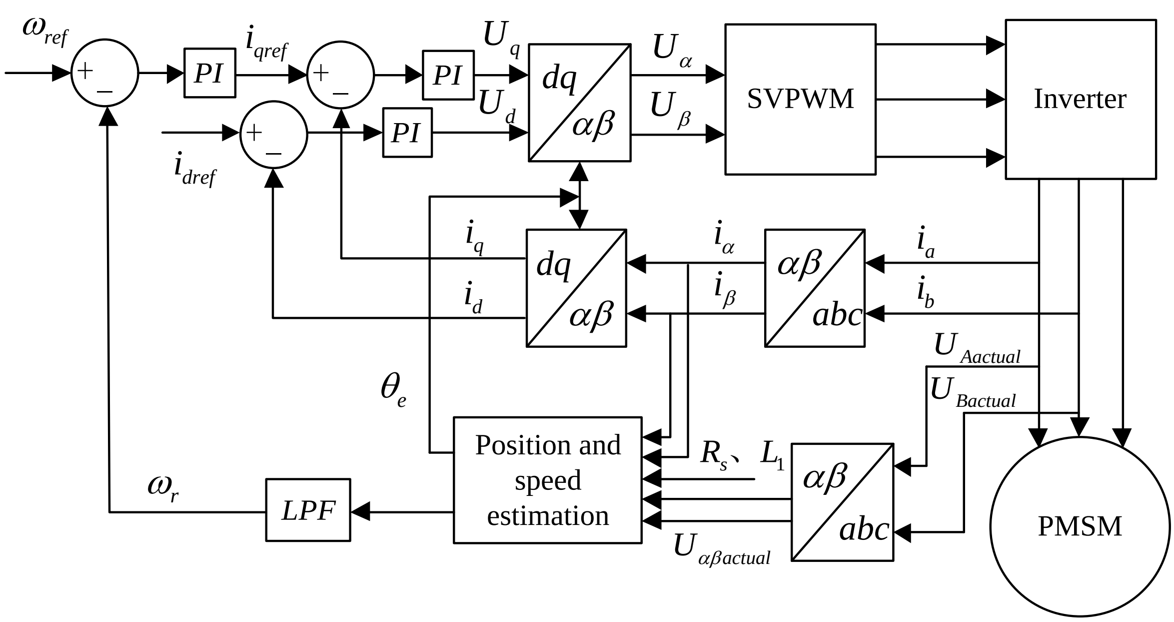

Figure 1. The principle of PMSM closed-loop sensorless control.

In figure 1, the PMSM instruction speed ω_{ref} and d axis instruction current i_{dref} are given externally. And then, the instruction speed and the estimated actual speed ω_r pass through the PI controller to output q axis instruction current i_{qref}. After that, the d-q axis instruction voltages U_{dq} of inverter are obtained from the PI control of instruction current i_{dqref} and the actual current i_{dq}. The estimated rotor electrical angle θ_e of PMSM is used to convert U_{dq} into $U_{\alpha\beta}$. Finally, the SVPWM algorithm converts $U_{\alpha\beta}$ into instruction PWM signal of inverters. In addition, θ_e is also used to convert the actual current of the motor from i_{abc} to i_{dq}.

3. Problems and Solutions of BEMF Method

Although the principle of BEMF method for estimating PMSM rotor position and speed is simple, there are still some problems in practical application. This part will analyze these problems and propose feasible solutions.

(1) Integral zero drift.

In equation (5), if the flux information is obtained by using pure integrator, there will be problems of DC offset and initial value of integration, which will lead to great errors in estimating rotor position and speed. In view of this phenomenon, a simple and effective elimination method is to average the maximum and minimum value of a sine flux cycle to obtain the current flux zero drift value, and subtract the zero drift value in the next cycle. The expression can be written as

$$\begin{aligned} \psi_{\alpha\beta offset} &= \frac{1}{2}(\psi_{\alpha\beta\min} + \psi_{\alpha\beta\max}) \\ \psi_{\alpha\beta} &= \int (u_{\alpha\beta} - Ri_{\alpha\beta})dt - \psi_{\alpha\beta offset} \end{aligned} \tag{8}$$

In equation (8), $\psi_{\alpha\beta offset}$ is the current flux zero drift value, $\psi_{\alpha\beta max}$ and $\psi_{\alpha\beta min}$ are the maximum and minimum value of a sine flux cycle.

(2) Fluctuation of speed estimation.

In the speed estimation of equation (7), dt is the switching period of the inverter, and its value is very small, usually tens of microseconds to hundreds of microseconds. This means that if the estimated position fluctuates slightly, the estimated speed will change dramatically, resulting in instability of the control system. The common method is to calculate the average value of the estimated speed every few switching cycles and use the obtained speed after low-pass filtering for system control. The expression can be written as

$$\omega_r = \frac{\theta_e(t) - \theta_e(t - nT_s)}{n_p n T_s} \tag{9}$$

In equation (9), t is defined as the current moment, T_s is the switching period value of the inverter, and n is the number of interval periods for speed estimation.

(3) Influence of PMSM parameters.

The PMSM parameters used in the BEMF method include stator resistance and inductance. The thermal effect and skin effect will change the stator resistance, and the magnetic saturation effect of inductance will also change the inductance. When the motor operates under light load and small current, these two parameters change little and have no influence on the position and speed estimation. However, when the current is relatively large, the resistance and inductance change greatly, and the corresponding parameter identification algorithm should be combined to make the position and speed estimation more accurate.

(4) Application limitation of BEMF method.

The BEMF method has good speed and position tracking effect over 10% rated speed of PMSM, but the estimation result is unstable in low speed region (below 5% rated speed), which easily causes the rotor to be out of step or locked during start-up. In addition, due to the amplitude of

PMSM back EMF is proportional to the rotational speed, the BEMF method cannot estimate the rotor position and speed when PMSM is stationary. Therefore, to achieve the full speed range of PMSM operation, the BEMF method needs to be combined with other methods.

4. Conclusion

This paper mainly discusses the application of BEMF method in rotor position and speed estimation of PMSM. Firstly, the principle of estimating rotor position and speed based on BEMF method is deduced by PMSM mathematical model, and on this basis, the closed-loop control system of PMSM is designed. Then the paper points out the problems of integral zero drift, unstable speed estimation and variation of PMSM parameters when estimating rotor position and speed by BEMF method in practice, and puts forward corresponding solutions.

Acknowledgments

This work was financially supported by the Fundamental Research Funds for the Central Universities (HIT.NSRIF.201705) and Natural Science Foundation of Shandong Province (ZR2017MEE011).

References

[1] M. Seilmeier, B. Piepenbreier, Sensorless Control of PMSM for the Whole Speed Range Using Two-Degree-of-Freedom Current Control and HF Test Current Injection for Low-Speed Range, J. Sci. 30 (2015) 4394 - 4403.

[2] Q. P. Tang, A. Shen, X. Luo, PMSM Sensorless Control by Injecting HF Pulsating Carrier Signal into ABC Frame, J. Sci. 32 (2017) 3767 - 3776.

[3] G. Zhang, G. Wang, D. G. Xu, ADALINE Network Based PLL for Position Sensorless Interior Permanent Magnet Synchronous Motor Drives, J. Sci. 32 (2016) 1450 - 1460.

[4] Z. Shang, R. X. Zhao, R. Z. Dou, Research on sensorless control method of PMSM based on an adaptive sliding mode observer, J. Proceedings of the CSEE, 27 (2007) 23 - 27.

[5] Q. L. Wang, C. W. Chong, X. Zhang, Variable-structure MRAS speed identification for permanent magnet synchronous motor, J. Proceedings of the CSEE, 28 (2008) 71 - 75.

[6] M. N. Uddin, M. M. Rashid, M. Rubaiyat, Comparison of position sensorless control based back-EMF estimators in PMSM [C]// International Conference on Computer & Information Technology. IEEE, 2016.