

# Sensorless Control Based on Search Coils for Six-Phase Permanent Magnet Synchronous Motor



Guangyi LI, Zhenzhong Su, Xinqiang Yi, and Bin Pan

**Abstract** Traditional sensorless control has the problem that the accuracy of rotor position estimation depends heavily on the precise motor parameters. In this paper, a sensorless control method based on search coils are proposed for six-phase permanent magnet synchronous motor to eliminate the interference of motor parameters on rotor position estimation. Firstly, the mathematical model of the search coils is described, and the key inductance parameters of the search coils are deduced. Secondly, on the basis of analyzing the induced potential of the search coils, a potential compensation term was introduced to eliminate the potential interference of the transformer under different load conditions, and the rotor position angle was calculated based on the phase-locked loop (PLL). Finally, the effectiveness and feasibility of the control algorithm are verified by simulation and experiment.

**Keywords** Six-phase permanent magnet synchronous motor · Search coils · Sensorless control · Phase-locked loop

---

G. LI · Z. Su · X. Yi (✉)

National Key Laboratory of Electromagnetic Energy, Wuhan 430033, China  
e-mail: [yixinqiang86@163.com](mailto:yixinqiang86@163.com)

B. Pan

College of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

© Beijing Paiké Culture Commu. Co., Ltd. 2023

Q. Yang et al. (eds.), *The proceedings of the 10th Frontier Academic Forum of Electrical Engineering (FAFEE2022)*, Lecture Notes in Electrical Engineering 1048,  
[https://doi.org/10.1007/978-981-99-3404-1\\_72](https://doi.org/10.1007/978-981-99-3404-1_72)

# 1 Introduction

## 1.1 A Subsection Sample

High power density, high adaptability, high reliability, high precision, low emission and multi-functional composite are the target requirements of motor system performance for the development of energy power and transportation [1]. Multi-phase permanent magnet synchronous motor (PMSM) not only has the advantages of high power density, fast dynamic response, high efficiency and large torque inertia ratio, but also can increase the output power of the motor and have the ability of fault-tolerant operation without increasing the power level of the power device. It has broad application prospects in ship electric propulsion, multi-electric/all-electric aircraft and rail transit [2].

Accurate rotor position information is the key to achieve high performance control of PMSM. Position sensors are often installed on the motor shaft to detect the rotor position of the motor in real time, such as photoelectric encoder, resolver and Hall sensor. The use of position sensors not only increases the cost and volume of the system, but also reduces the immunity and reliability of the system. More importantly, some special applications cannot install position sensors, such as shaftless propulsion systems. Therefore, the sensorless control of PMSM is widely used in various industrial occasions [3],

The position sensorless control based on the search coils has attracted attention due to its low cost, strong immunity and independence of motor parameters. The search coil is a group of windings laid in the stator slot of the motor. It was first used to obtain the distribution of the air gap magnetic field [4, 5], and then extended to fault diagnosis [6, 7] and sensorless control [8–10]. Classical sensorless control includes high frequency injection method [11], back electromotive force method [12], model reference adaptive observer method [13, 14] and so on. Because the observation accuracy of these algorithms depends heavily on the accuracy of the motor parameters, it is difficult to guarantee the control effect in the case of complex working conditions and high reliability requirements. Since the search coil does not participate in energy conversion, the parameters are not easy to change. Therefore, the position estimation accuracy based on the search coil is not sensitive to the change of motor parameters. Consistent with the classical sensorless control, the sensorless control based on the search coils can calculate the position information of the motor at zero low speed and medium high speed respectively through the salient pole model and fundamental wave model of the motor. The method based on the salient pole model obtains the position signal by injecting high frequency voltage signal into the search coils. Reference [15] injected high-frequency square wave pulse signals into three search coils on the stator slot of the switched reluctance motor, and estimated the rotor position by using the mutual inductance characteristics between the main winding and the search coils generated by the convex polarity of the rotor. The method based on the fundamental wave model is to obtain the rotor position of the motor by solving the air gap magnetic field induced by the search coils. In Reference [16], a

direct rotor position calculation method based on the back electromotive force (EMF) of the search coils are proposed for the permanent magnet synchronous motor, which eliminates the error caused by the change of parameters such as stator resistance. At present, the search coils are mainly used for fault analysis, and the research on position sensorless is rarely involved. In view of its application advantages in high reliability occasions, it is worth further study.

In this paper, a position estimation algorithm based on search coils and phase-locked loop is proposed for six-phase PMSM, so as to realize sensorless control. On the basis of expounding the mathematical model of search coils and deducing the key inductance parameters, the compensation term is introduced to eliminate the interference of transformer electromotive force, and the rotor position angle is calculated based on phase-locked loop. Simulation and experimental results verify the feasibility and effectiveness of the control algorithm.

## 2 Mathematical Model of Six-Phase PMSM

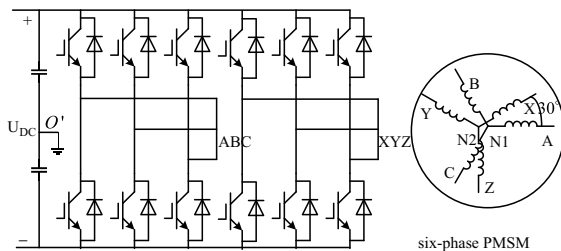
The driving circuit of the six-phase PMSM is shown in Fig. 1. The six-phase winding consists of two sets of three-phase windings with a phase shift of 30°.

Six-phase PMSM can be equivalent to two three-phase PMSM decoupling control by double *dq* coordinate transformation, which has a clear physical concept. With the application of the constant amplitude transformation matrix, the mathematical motor model of the ABCXYZ coordinate is transformed into the  $\alpha_1\beta_1$  and  $\alpha_2\beta_2$  coordinate systems, and then transformed into the  $d_1q_1$  and  $d_2q_2$  coordinate systems with the application of the rotating coordinate transformation matrix. The relationship between the various coordinate systems is shown in Fig. 2.

In the double *dq* coordinate system, the voltage equation of the six-phase PMSM can be expressed as:

$$\begin{bmatrix} u_{d1} \\ u_{q1} \\ u_{d2} \\ u_{q2} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_s & 0 \\ 0 & 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} + p \begin{bmatrix} \psi_{d1} \\ \psi_{q1} \\ \psi_{d2} \\ \psi_{q2} \end{bmatrix} + \omega_e \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \psi_{d1} \\ \psi_{q1} \\ \psi_{d2} \\ \psi_{q2} \end{bmatrix} \quad (1)$$

**Fig. 1** Driving circuit structure of six-phase PMSM



six-phase PMSM

where  $u_{d1}, u_{q1}, u_{d2}, u_{q2}$  are the DC voltage components in two sets of synchronous rotating coordinate system respectively.  $\psi_{d1}, \psi_{q1}, \psi_{d2}, \psi_{q2}$  are the corresponding flux components;  $i_{d1}, i_{q1}, i_{d2}, i_{q2}$  are the corresponding current components;  $\omega_e$  is the electric angular velocity;  $p$  is a differential operator.

The flux linkage equation is expressed as:

$$\begin{bmatrix} \psi_{d1} \\ \psi_{q1} \\ \psi_{d2} \\ \psi_{q2} \end{bmatrix} = \begin{bmatrix} L_d & 0 & L_{dd} & 0 \\ 0 & L_q & 0 & L_{qq} \\ L_{dd} & 0 & L_d & 0 \\ 0 & L_{qq} & 0 & L_q \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \\ i_{d2} \\ i_{q2} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \end{bmatrix} \psi_f \quad (2)$$

where  $\psi_f$  is the flux linkage of permanent magnet;  $L_d$  is a direct axis synchronous inductance;  $L_{dd}$  is the mutual inductance between two sets of d-axis windings;  $L_q$  is quadrature axis synchronous inductance;  $L_{qq}$  is the mutual inductance between two sets of q-axis windings.

The torque equation is expressed as:

$$T_e = 1.5 p_n (i_{q1} \psi_{d1} - i_{d1} \psi_{q1} + i_{q2} \psi_{d2} - i_{d2} \psi_{q2}) \quad (3)$$

### 3 Search Coil Principle

#### 3.1 Search Coils Mathematical Model

The search coils proposed in this paper is two windings with orthogonal electrical angles. The rotor position estimation can be realized by its induced potential in the open circuit. The potential is composed of the transformer potential generated by the alternating magnetic field of each phase stator winding and the rotating potential generated by the rotation of the permanent magnet. It can be expressed as:

$$\begin{bmatrix} u_{w1} \\ u_{w2} \end{bmatrix} = \mathbf{M}_{2 \times 6} \mathbf{p} \mathbf{i}_{6 \times 1} + \psi_f \omega_e \begin{bmatrix} k \cos(\theta_e + p_n \Delta\theta) \\ k \cos(\theta_e + p_n \Delta\theta + \frac{\pi}{2}) \end{bmatrix} \quad (4)$$

where  $u_{w1}$  and  $u_{w2}$  represent the induced electromotive force of the search coil w1 and w2 respectively; the coefficient  $k$  depends on the amplitude of the induced potential of the search coil under no-load condition.  $\Delta\theta$  is the mechanical angle between the search coil w1 and the A-phase winding of the six-phase PMSM, which is determined by the position of the search coils added to the stator.

$$\mathbf{i}_{6 \times 1} = [i_A \ i_B \ i_C \ i_X \ i_Y \ i_Z]^T$$

$$\mathbf{M}_{2 \times 6} = \begin{bmatrix} M_{Aw1} & M_{Bw1} & M_{Cw1} & M_{Xw1} & M_{Yw1} & M_{Zw1} \\ M_{Aw2} & M_{Bw2} & M_{Cw2} & M_{Xw2} & M_{Yw2} & M_{Zw2} \end{bmatrix} = \begin{bmatrix} \mathbf{M}_1 \\ \mathbf{M}_2 \end{bmatrix}$$

where  $M_{ij}$  is the mutual inductance parameter value between the  $i$ -phase winding of the stator and the search coil  $w_j$ .  $i$  represents each phase winding of the stator, and  $w_j$  represents the search coil  $w_1$  and  $w_2$ .  $\mathbf{M}_1$  is the row vector composed of the mutual inductance parameters between the search coil  $w_1$  and the stator windings;  $\mathbf{M}_2$  is the row vector composed of the mutual inductance parameters between the search coil  $w_2$  and the stator windings.

Due to the large difference between the number of turns of the search coil and the number of turns of the stator winding, usually up to dozens of times, the mutual inductance value is not equal to the simple product of the stator self-inductance and the angle cosine value, which needs to be re-derived. At the same time, special attention should be paid to the influence of pitch factor and turns.

The space fundamental magnetic potential  $F_{ag1}$  in the two-pole motor is:

$$F_{ag1} = \frac{4}{\pi} \frac{Ni}{2} \cos \theta_a \tag{5}$$

where  $N$  is the number of turns of the stator winding;  $\theta_a$  is the distribution angle with the stator coil magnetic pole axis as the reference zero point.

The corresponding air gap flux density  $B_{ag1}$  is:

$$B_{ag1} = \mu_0 \frac{F_{ag1}}{g} = \frac{2\mu_0 Ni}{\pi g} \cos \theta_a \tag{6}$$

where  $\mu_0$  is the air permeability;  $g$  is the air gap length.

The fundamental air gap flux  $\phi_p$  per pole is:

$$\phi_p = l \int_{-\pi/2}^{\pi/2} B_{ag1} r d\theta_a \tag{7}$$

where  $r$  is the radius of the rotor;  $l$  is the axial length of air gap.

The air gap inductance  $L$  of the coil is:

$$L = \frac{\psi}{i} = \frac{N\phi_p}{i} = \frac{4\mu_0 N^2 l r}{\pi g} \quad (8)$$

For the multi-pole distribution winding with the pole pair of  $p_n$  and the number of turns in series of  $N_l$  and the winding coefficient of  $k_{w1}$ ,  $N$  is replaced by the effective number of turns per pole ( $k_{w1}N_l/p_n$ ) in Formula (8), and the air gap inductance can be obtained as:

$$L = \frac{4\mu_0 l r}{\pi g} \left( \frac{k_{w1} N_l}{p_n} \right)^2 \quad (9)$$

Therefore, for the two sets of windings with winding distribution factors of  $k_{w1}$  and  $k_{w2}$  and turns of  $N_l$  and  $N_2$  respectively in the same motor when the magnetic pole axis insulation angle is  $\alpha$ , the mutual inductance of the two sets of windings is:

$$M_{12} = \frac{4\mu_0}{\pi} \left( \frac{k_{w1} N_l}{p_n} \right) \left( \frac{k_{w2} N_2}{p_n} \right) \frac{l r}{g} \cos \alpha \quad (10)$$

The general ratio between mutual inductance  $M_{12}$  and air gap inductance  $L$  is:

$$\frac{M_{12}}{L} = \frac{k_{w2} N_2}{k_{w1} N_l} \cos \alpha \quad (11)$$

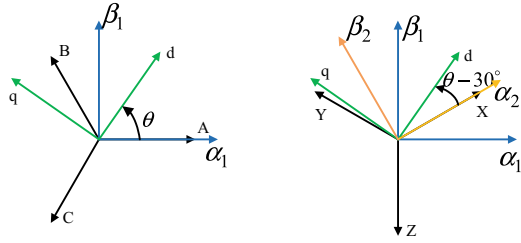
According to Eq. (11), the mutual inductance parameter value between the stator winding and the search coil can be calculated by the air gap inductance of each stator winding.

### 3.2 Rotor Position Estimation Based on Search Coils

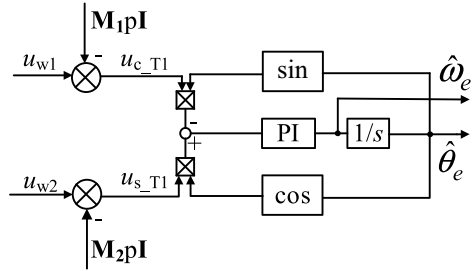
The induced potential of the search coils consists of two parts, which are the transformer potential of the first term and the moving potential of the second term in Eq. (4). The information of the rotor position estimation only exists in the moving potential, and as the load increases, the amplitude of the transformer potential will also increase, and the proportion of the moving potential will decrease, so the interference to the rotor position estimation will also increase. Therefore, it is necessary to compensate the induced potential of the search coils to eliminate the transformer potential.

$$\begin{bmatrix} u_{c\_T1} \\ u_{s\_T1} \end{bmatrix} = \begin{bmatrix} u_{w1} \\ u_{w2} \end{bmatrix} - \mathbf{M}_{2 \times 6} \mathbf{p}_{6 \times 1} = \psi_f \omega_e \begin{bmatrix} k \cos(\theta_e + p_n \Delta\theta) \\ k \cos(\theta_e + p_n \Delta\theta + \frac{\pi}{2}) \end{bmatrix} \quad (12)$$

**Fig. 2** Double dq coordinate transformation of six-phase PMSM



**Fig. 3** Control block diagram of rotor position estimation based on search coils



The rotor position angle can be obtained by inputting the induced potential after potential compensation into the phase-locked loop. In the induced electromotive force, the sine and cosine functions of  $\hat{\theta}_e$  are multiplied by the cosine and sine of the estimated value of the rotor position, and the error  $\varepsilon$  between the actual value and the estimated value is:

$$\varepsilon = \sin \theta_e \cos \hat{\theta}_e - \cos \theta_e \sin \hat{\theta}_e = \sin(\theta_e - \hat{\theta}_e) \tag{13}$$

Finally,  $\varepsilon$  can output the estimated rotor position through the PI regulator. The rotor position estimation control block diagram based on the search coils is shown in Fig. 3.

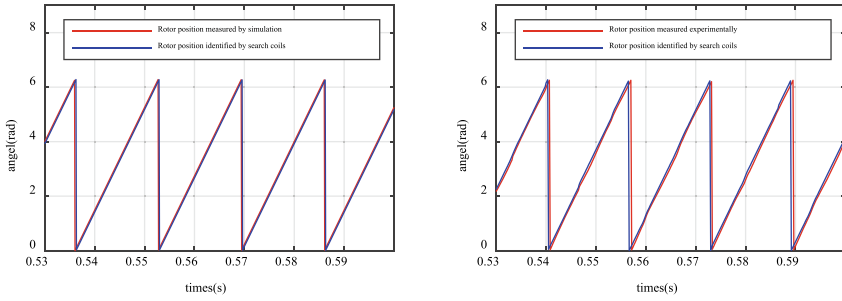
The six-phase PMSM sensorless vector control block diagram based on the search coils are shown in Fig. 4. The rotor position estimation and speed estimation are obtained by processing the search coils voltage  $\mathbf{u}$  and the motor phase current  $\mathbf{i}$  obtained by sampling. The rotor position estimation is used to realize the coordinate transformation, which is used to realize the double closed-loop vector control of the motor speed and current based on  $i_{d1}^* = 0, i_{d2}^* = 0$ .

### 4 Simulation and Experimental Verification

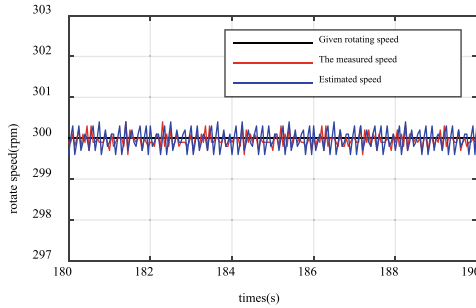
In order to verify the effectiveness and feasibility of the proposed control strategy, a model is built for simulation verification, and compared with the experimental results of the actual six-phase permanent magnet synchronous motor. The six-phase PMSM parameters used are shown in Table 1.







(a) Rotor position estimation results in simulation and experiment

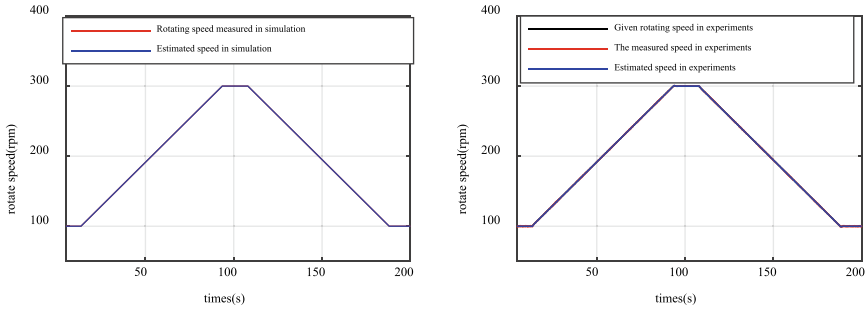


(b) Steady-state speed experimental results

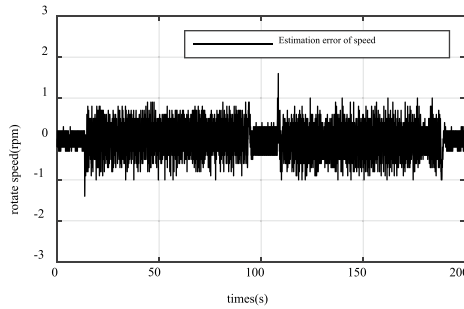
Fig. 5 Simulation and experiment results in steady state process

### 4.2 Comparative Analysis

The position tracking error based on the search coils is further extracted from the experimental waveform. As shown in Table 2, the position error is 0.15 rad. For the static and dynamic position tracking error performance of multi-phase permanent magnet motor sensorless control, Table 2 shows that the maximum steady-state position error is 2.39%, the steady-state speed error is less than 1 rpm, and the dynamic speed error is less than 2 rpm, which more effectively verifies the feasibility of rotor position estimation of permanent magnet motor based on search coils.



(a) Speed curve in simulation and experiment



(b) The speed error curve in the experiment

**Fig. 6** Simulation and experiment results of dynamic speed up and down process

**Table 2** Position tracking error analysis based on search coils

Project	Experimental analysis results of position tracking error
Experimental steady-state speed error	0–1 rpm
Experimental dynamic speed error	0–2 rpm
Experimental position error	0.15 rad

## 5 Conclusion

The sensorless control of six-phase PMSM can be realized based on the search coils. And the rotor position obtained based on the search coils is independent of parameters such as stator resistance. Therefore, the temperature rise of the motor and the change of the environment will not affect the accuracy of position estimation. This provides a new idea for rotor position estimation of multiphase permanent magnet motors applied to shaftless propulsion systems.

## References

1. Ma, W., Wang, D., Cheng, S., et al.: Common basic scientific problems and development of leading-edge technology of high performance motor system. *Proc. CSEE* **36**(8), 11. (in Chinese)
2. Ma, W.: Thoughts on the development of frontier technology in electrical engineering. *Trans. China Electrotech Soc.* **36**(22), 10. (in Chinese)
3. Wang, S., Cao, D., Yang, Y., et al.: Sensorless control of PMSM with positive and negative high frequency pulse voltage signal injection. *Trans. China Electrotech. Soc.* **35**(S01), 8. (in Chinese)
4. Wang, Z.Q., Liu, X.X.: Nonlinear internal model control for bearingless induction motor based on neural network inversion. *Acta Automatica Sinica* **39**(4), 433–439 (2013)
5. Zhang, F., Chen, J., Liu, G., et al.: The nonlinear control of bearingless induction motors based on the motor rotor flux orientation. *Proc. CSEE* **23**(3), 4 (2003). (in Chinese)
6. Geng, T.: Research on bearing fault of induction motor based on search coils. *Dalian Mar. Univ.* 2016. (in Chinese)
7. Da, Y., Shi, X., Krishnamurthy, M.: A new approach to fault diagnostics for permanent magnet synchronous machines using electromagnetic signature analysis. *IEEE Trans. Power Electron.* **28**(8), 4104–4112 (2012)
8. Keysan, O., Ertan, H.B.: Higher order rotor slot harmonics for rotor speed & position estimation. In: 2010 12th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), IEEE Xplore, 2010
9. Yao, Z., Yi, X., Hu, J., et al.: Rotor position estimation of permanent magnet motor based on search coils. *MICROMOTORS* **54**(7), 4 (2021). (in Chinese)
10. Im, J.H., Hur, J.: Proposing new planar-type search coil for permanent magnet synchronous motor: design and application for position estimation. *IEEE Access* **9**, 129078–129087 (2021)
11. Zhao, W., Liu, H., Tao, T., et al.: MTPA control of sensorless IPMSM based on virtual signal and high-frequency pulsating signal injection. *Trans. China Electrotech. Soc.* **36**(24), 9 (2021). (in Chinese)
12. Liu, J., Xiao, F., Shen, Y., et al.: Position-sensorless control technology of permanent-magnet synchronous motor-a review. *Trans. China Electrotech. Soc.* **32**(16), 13 (2017). (in Chinese)
13. Li, Z., An, J., Xiao, Y., et al.: Design of model predictive control system for permanent magnet synchronous linear motor based on adaptive observer. *Trans. China Electrotech. Soc.* **36**(6), 11. (in Chinese)
14. Song, W., Ren, H., Ye, H.: Position sensorless control of dual three phase permanent magnet synchronous motor based on MRAS. *Proc CSEE*, **42**(3): 10.1. (2022). (in Chinese)
15. Xu, F.: Research on rotor position estimation technology of switched reluctance motor with built-in search coils. *Nanjing University of Information Science and Technology*, 2018. (in Chinese)
16. Yao, D., Xiaodong, S., Krishnamurthy, M.: A Novel Universal sensor concept for survivable PMSM drives. *IEEE Trans. Power Electron PE* **28**, 5630–5638 (2013)