# Sensorless Control of Permanent Magnet Synchronous Motor with Stator Flux Estimation

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***Abstract*—As the mechanical sensor of PMSM easily break out, attentions are paid to the PMSM sensorless control method. In this paper, a modified stator flux methods based on the active flux is proposed, which can estimate the rotor position and speed of the motor after accurate stator flux estimation using active flux. This method is of simple calculation and less dependence on motor parameters, and it suits for both SPMSM and IPMSM. The simulation results and experimental results show the method can estimate both the rotor position and speed in either abrupt load torque or variable speed condition.**

***Index Terms*—PMSM, Sensorless control, Stator flux estimation, Active flux**

## I. INTRODUCTION

As the development of permanent magnet material, the applications of permanent magnet synchronous motors (PMSM) is becoming more and more abroad recently. The PMSMs with permanent magnet rotor instead of electrical excitation coil simplify the structure, thus bring the advantages of small size, light weight, high power density, high efficiency, structural diversification and so on.

The precise position and speed data are necessary for high performance vector control. Usually, the rotor position can be detected by a encoder. But the mechanical speed and position sensors inside PMSM are strict to the environment, and susceptible to vibration, humidity and other environmental factors which lead to limit scope of application. To instead of using position sensors, a sensorless control method has been developed for control of the motor using the estimated values of the position and speed by the measurement of voltage and current of motor. The extended Kalman filter and adaptive observer are used for sensorless control of PMSM but the computationally intensive limit its application[1]-2]. The sliding-mode observer (SMO) is widely used in PMSM control but the low-pass filter has to be added to reduce the chattering problem.

Stator-Flux(back-EMF)-based sensorless control of permanent magnet synchronous machines is preferred in many industrial applications due to its simplicity and easy to implementation., this method is most reliable in the medium-to high-speed range. However, for interior PMSMs with different d and q axis inductance, there are some difficulties in rotor position estimation from stator flux.

In this paper, we adopt the stator flux estimation method based on a modified integrator which integrates the stator EMF to the stator flux. Using the concept of active flux, the rotor position could be calculated directly.

## II. PMSM MATHEMATIC MODEL

The stator voltage equation in the rotating dq two phase rotor reference frame can be expressed as follow:

$$\begin{pmatrix} u_d \\ u_q \end{pmatrix} = R_s \begin{pmatrix} i_d \\ i_q \end{pmatrix} + p \begin{pmatrix} \psi_d \\ \psi_q \end{pmatrix} + \omega_r \begin{pmatrix} -\psi_q \\ \psi_d \end{pmatrix} \tag{1}$$

The flux linkage in dq reference frame is

$$\begin{pmatrix} \psi_d \\ \psi_q \end{pmatrix} = \begin{pmatrix} L_d & 0 \\ 0 & L_q \end{pmatrix} \begin{pmatrix} i_d \\ i_q \end{pmatrix} + \psi_f \begin{pmatrix} 1 \\ 0 \end{pmatrix} \tag{2}$$

The torque equation can be expressed as

$$T_e = p_n \left[ \psi_f i_q + \left( L_d - L_q \right) i_d i_q \right] \tag{3}$$

Equation (3) can be rewritten as,

$$T_e = p_n \left[ \psi_f + \left( L_d - L_q \right) i_d \right] i_q \tag{4}$$

where,

$u_d, u_q$ : d-axis and q-axis stator voltage;

$i_d, i_q$ : d-axis and q-axis stator current ;

$\psi_d, \psi_q$ : d-axis and q-axis stator flux;

$L_d$=$L_q$ : d-axis and q-axis inductance;

$\omega_r$ : rotor electrical angular velocity;

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$\psi_f$ : rotor magnet flux;

$R_s$ : stator resistance ;

$p$ : differential operator.

It is obviously to conclusion that the equation in the bracket $\left(\psi_f + \left(L_d - L_q\right) i_d\right)$ is same direction with the rotor flux, as the rotor flux $\psi_f$ and the d-axis current $i_d$ are all belong to the d-axis, while the $L_d$ , $L_q$ are all constant nothing to do with rotor position. So we define it as active flux $\vec{\psi}_d$ [8][9], the equation is expressed as follow,

$$\psi_d = \psi_f + (L_d - L_q) i_d \tag{5}$$

To the SPMSM( $L_d = L_q$ ), $\psi_d = \psi_f$ ;

To the IPMSM( $L_d < L_q$ ), $\psi_d = \psi_f + (L_d - L_q) i_d$ .

According to the defintion of active flux, the torque equation can be rewritten as,

$$T_e = p_n \psi_d i_q \tag{6}$$

The vector diagram of PMSM is shown in Fig.1 .

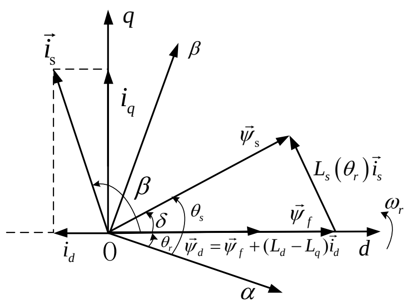


Fig. 1 Vector diagram of active flux in dq reference frame

## III. SPEED AND POSITION ESTIMATING METHOD BASED ON ACTIVE FLUX

### A. Stator Flux Estimation

According to the PMSM voltage vector equation,

$$\vec{u}_s = R\vec{i}_s + \frac{d\vec{\psi}_s}{dt} \tag{7}$$

The stator flux $\vec{\psi}_s$ can be expressed as,

$$\vec{\psi}_s = \int (\vec{u}_s - R_s \vec{i}_s) dt \tag{8}$$

Transform to the two-phase stationary reference frame can be expressed as,

$$\begin{cases} \psi_\alpha = \int (u_\alpha - R_s i_\alpha) dt \\ \psi_\beta = \int (u_\beta - R_s i_\beta) dt \end{cases} \tag{9}$$

Where, $\psi_\alpha$ , $\psi_\beta$ are the α-axis and β-axis components of stator flux; $u_\alpha$ , $u_\beta$ are the α-axis and β-axis components of stator voltage; $i_\alpha$ , $i_\beta$ are the α-axis and β-axis components of stator current.

The block diagram of PMSM sensorless control is shown in Fig.2.

The integration from stator EMF to stator flux is only related to the stator resistance parameters, so when higher precision is needed, we can combine the method with stator resistance on-line identification.

### B. Speed and Position Estimation

After the accurate observation of stator flux vector, we need to estimate the rotor position and speed from it. The mainly solution can be divided into two types:

1) Estimation method based on load angle[10];
2) Estimation method based on iteration[11].

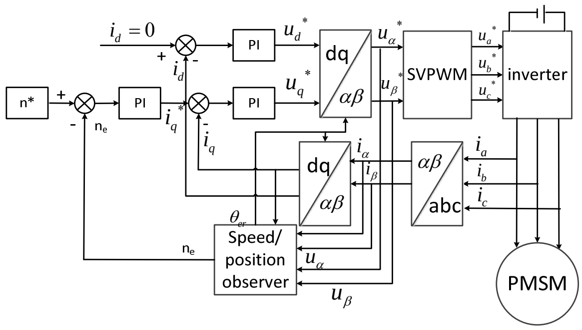



Fig. 2 Block diagram of PMSM sensorless control

But neither of them could match the demand of traction motor, so we adopt a position estimating method based on active flux.

After the definition of active flux vector $\vec{\psi}_d$ , equation (5) can be rewritten as,

$$\vec{\psi}_d = \psi_f + L_d i_d + jL_q i_q - L_q i_d - jL_q i_q \tag{10}$$

Combine the last two terms,

$$\vec{\psi}_d = \psi_f + L_d i_d + jL_q i_q - L_q \left(i_d + j i_q\right) \tag{11}$$

The active flux is,

$$\vec{\psi}_d = \vec{\psi}_s - L_q \vec{i}_s \tag{12}$$

From equation (12), it is shown that the relationship between active flux $\vec{\psi}_d$ and stator flux $\vec{\psi}_s$ is simple, the only motor parameters affected is the q-axis inductance, and it fits for both SPMSM and IPMSM. As the direction of active flux and rotor flux, the rotor position angle $\theta_r$ is same as angle between $\vec{\psi}_d$ and α-axis.

Substituting stator flux estimation equation (8) into active flux equation (12),

$$\vec{\psi}_d = \int (\vec{u}_s - R_s \vec{i}_s) dt - L_q \vec{i}_s \tag{13}$$

Transforming into the static two-phase reference frame,

$$\begin{aligned} \psi_{d\alpha} &= \int (u_\alpha - R_s i_\alpha) dt - L_q i_\alpha \\ \psi_{d\beta} &= \int (u_\beta - R_s i_\beta) dt - L_q i_\beta \end{aligned} \tag{14}$$

Estimating equation of rotor position angle $\theta_r$ is,

$$\theta_r = \arctan\frac{\psi_{d\beta}}{\psi_{d\alpha}} = \arctan\frac{\int (u_\beta - R_s i_\beta)dt - L_q i_\beta}{\int (u_\alpha - R_s i_\alpha)dt - L_q i_\alpha} \quad (15)$$

As is shown above, the active flux esitimating method is simple in calculation and fast in response, the only problem of it may caused by the integration algorithm. Using the pure integrator may bring about integrator saturation and DC bias problem, while using the LPF would produce errors in both magnitude and phase angle. So we adopt the modified integrator for integration algorithm.

## IV. Simulation and Experimental Results

The proposed method is verified by numerical simulation and experimental situation.

### A. Simulation results

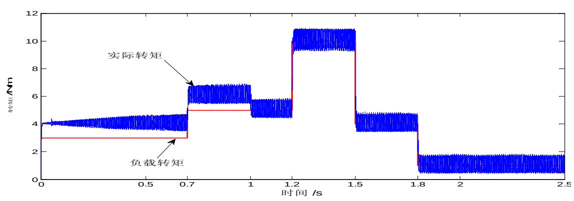
The simulation motor is a 6-pole internal permanent magnet synchronous motor (IPMSM), the parameters are shown in Tab.1 .

TABLE I
PARAMETERS OF PMSM IN SIMULATION

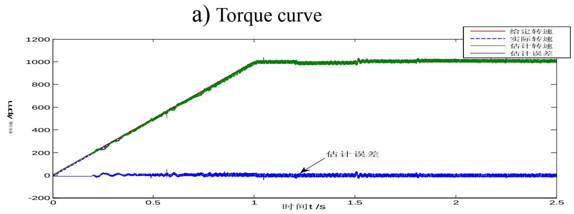
| Parameters | Value | Parameters | Value |
|---|---|---|---|
| Rated power | 1.5 kW | Stator resistance | 0.513 |
| Rated line voltage | 100 V | Voltage constant | 66.9 mV/rpm |
| Rated current | 9 A | d-axis inductance | 4.74mH |
| Rated speed | 1500 rpm | q-axis inductance | 9.51mH |
| Pole | 6 | Rotational inertia | 0.01 kg*m$^2$ |

As the stator flux is not suit for motor of low speed range, so when motor speed is under 200rpm, the actual speed delivered from speed and position sensor would be adopt for vector control, while motor speed is over 200rpm the active flux estimation value is adopt.

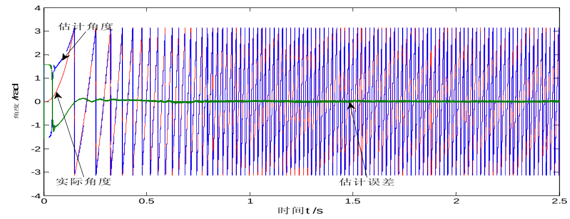
The PMSM starts from standstill to 1000rpm at a acceleration of 1000rpm/s and then keep the speed of 1000rpm, the load torque changes 4 times at 0.7s, 1.2s, 1.5s and 1.8s. The cut-off frequency of the LPF in the modified integrator changes as the estimating speed, keeping as 2 times as corresponding angular speed. Simulation results is shown as Fig.3.



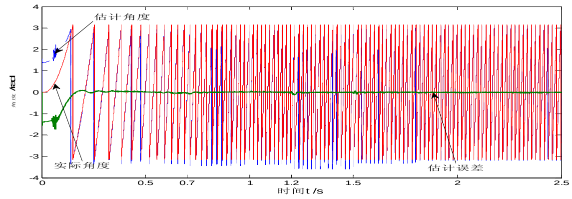

a) Torque curve




b) Speed curve




c) Rotor position curve

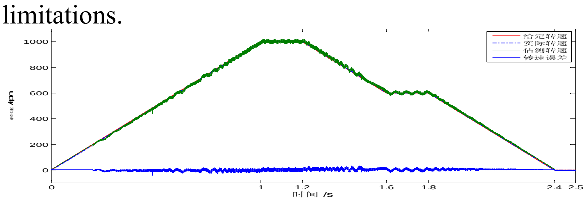



d) Rotor position curve of load angle estimation method

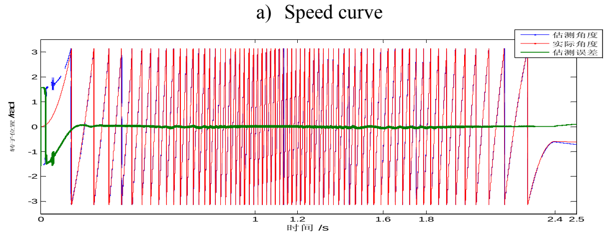
Fig. 3 Simulation results of sensorless control with constant speed and variable torque

Fig.3 shows simulation results of sensorless control with constant speed and variable torque. Fig.3(a),(b),(c) is the simulation results using the active flux method. At the starting procedure, rotor position esitmation error is great, so it is necessary to start with actual speed, the maximum speed estimation error at this procedure is within ±25rpm. After 2-3 period, while the motor speed is over 200rpm, the rotor position estimation error keeps in ±3°, so as that the speed estimation error keeps with in ±20rpm. The estimation errors would not grow as motor accelerates or load torque changes, which shows that this method would not be affected by the variation of load torque.

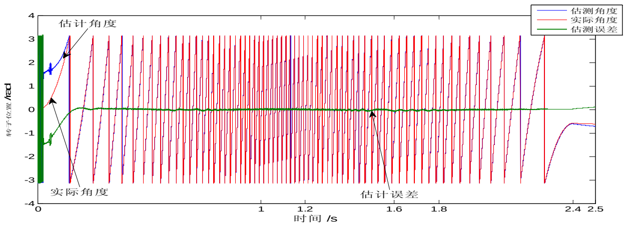
Fig.3(d) shows the rotor position simulation result of load angle estimation method under the same simulation condition. When motor load torque saltation, as the q-axis current cann't track the instruction q-axis current immediately, the position estimation error would become greater. When the load torque changes from 5Nm to 10Nm at 1.2s, the estimation error becomes ±9° at the point. After the current would track the instruction current, the error becomes ±4°. Otherwise, load angle of IPMSMs without zero d-axis current control strategies would be difficult to obtain, so this method has some limitations.




a) Speed curve




b) Rotor position curve




c) Rotor position curve with iteration method

Fig. 4 Simulation results of sensorless control with variable speed and constant torque

Fig.4 shows simulation results of sensorless control with constant torque and variable speed. Fig.4(a),(b) is the simulation results using the active flux method. During the whole constant torque and variable speed running procedure, the position estimation error would keep within ±3°, so as the speed estimation error keeps within ±20rpm.

Fig.4(c) shows the rotor position simulation result of iteration estimation method under the same simulation condition. During motor starting process, as the modified integrator starts, the rotor position estimation error is large. And the iteration method use the value of the moment before, so the large estimation error lead to great estimation error which would lead to moter reversal. This method is not suit for speed saltation condition, meanwhile the starting process.

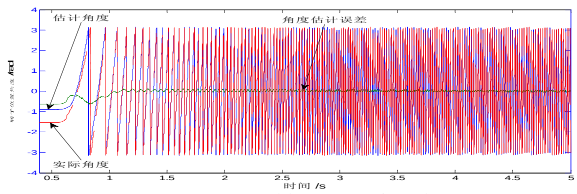
## *B. Experimental Results*

The experimental motor is a 5.5kW IPMSM, the parameters is shown as Tab.2.

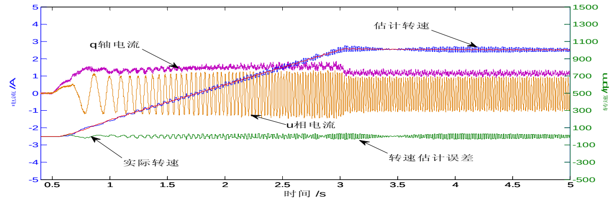
The motor starts from standstill to 1000rpm at a acceleration of 400rpm/s, then keeps the speed of 1000rpm, at last decelerate to stop. when motor speed is under 120rpm, the actual speed delivered from speed and position sensor would be adoptl, while motor speed is over 200rpm the active flux estimation value is adopt. The experimental results is shown in Fig.5.

TABLE II
PARAMETERS OF EXPERIMENTAL MOTOR

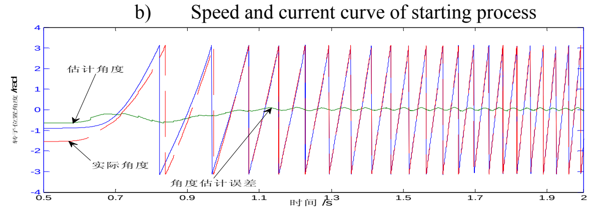
| Parameters | Value | Parameters | Value |
|---|---|---|---|
| Rated power | 5.5 kW | Rated torque | 35 Nm |
| Rated line voltage | 380 V | Pole | 6 |
| Rated current | 13 A | Stator resistance | 0.55 Ω |
| Rated frequency | 75 Hz | Voltage constant | 253.3 V/krpm |
| Rated speed | 1500 rpm | Line inductance | 17 mH |



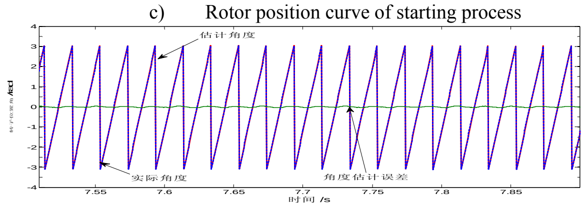

a) Rotor position curve of starting process



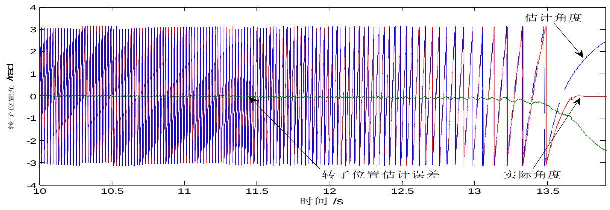

b) Speed and current curve of starting process



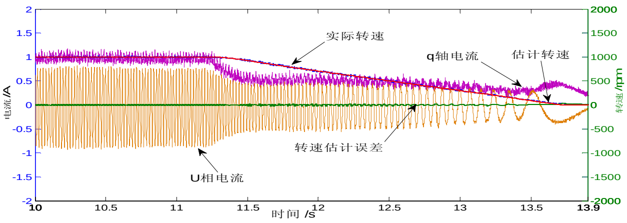

c) Rotor position curve of starting process



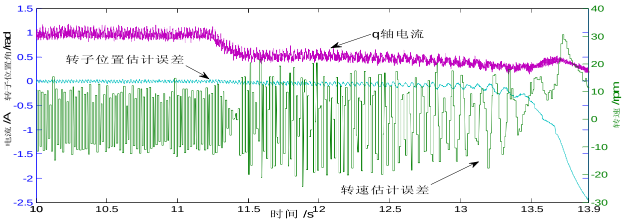

d) Speed and current curve of constant speed process




e) Rotor position curve of braking process




f) Speed and current curve of braking proces




g) Speed and current curve of braking proce

Fig. 5 Experimental results without load torque

Fig.5 is the experimental results without load torque adopting the active flux method. Fig.5(a),(b) is the rotor position curve of starting procedure. Motor rotates at 0.6s, the esitmation error converges within ±3° while speed estimation error keeps within ±20rpm at 1.1s. (d) is the rotor position of constant speed, the rotor position estimation error is ±2° at this period, while the speed estimation error is ±15rpm. (e),(f) is the rotor position and speed curve of braking procedure. During the deceleration to stop process, the position error becomes slightly larger to ±3°, comparing with errors in constant speed range.

Conclud from the two simulation results and experimental results, the PMSM sensorless control method based on active flux can achieve an accurate estimation of rotor position and speed both in variable speed and variable load torque cases.

## V. Conclusion

In this paper, a modified stator flux method based on active flux is proposed, which achieve an accurate estimation of rotor position and speed after staotor flux estimation. It is more simple than existing method, and is insensitive to the load torque and speed change. Besides, it suits for both SPMSM and IPMSM. Simulation and experimental results certify that this method can estimate rotor position and speed accurately in load torque or speed change condition.

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