Simulation of Sensorless Control of PMSM based on Zero-Sequence Carrier Injection with Improved Speed Estimation

Meera E., Prathibha P.K.

Abstract— A sensorless control method for surface mounted permanent magnet synchronous motor is discussed. This method uses magnetic saliencies to estimate the position of the rotor. A high frequency zero- sequence signal generated by space vector modulation is used as the carrier. It is applied to the motor by connecting the neutral point of motor to the dc link through a filter.The current response to the injected signal is analyzed for estimating the rotor position. In this paper, a phase-locked loop observer to estimate speed and to filter the estimated position is proposed. Thus the noise produced by position differentiation is eliminated. This method is validated using simulation.

Index Terms— Permanent magnet synchronous motor(PMSM), Field oriented control, sensorless control, carrier injection, phase locked loop.

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1 INTRODUCTION

The permanent magnet synchronous motor (PMSM) has been widely used in industrial applications due to its high performance characteristics. In the high-performance variable speed and precise position control applications, high-resolution rotor position information is required to execute field-oriented control algorithm. As a result, a resolver or encoder attached to the shaft of the rotor is typically used. These position sensors, however, increase the cost, inertia, and size of the PMSM drive system. Elimination of the shaft position sensor from the PMSM applications has resulted in the development of several techniques.

Sensorless control refers to a special type of motor control where the rotor position sensor is replaced by a mathematic algorithm which uses information from other sensors such as current sensors and voltage sensors.

An electromotive force (EMF) model has been used to estimate the rotor position and speed [1]. The rotor's position is contained in the EMF of the motor. The disadvantage of this method is that it involves complicated computations to obtain the EMF of the motor. Also this method cannot be used at low speed or standstill since EMF would be zero. A nonlinear observer has been proposed to estimate rotor position and speed. This method is dependent on mechanical parameters and noise [2].

An injecting-signal method has been used to detect the rotor position of the PMSM. This estimating method is not affected by the motor speed and load. This method uses the

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inductance variation with rotor position or magnetic saliency for estimating rotor position. Magnetic saliency can be caused either due to saliency of interior rotor or by saturation of stator iron by the rotor flux as in surface mounted PMSM. A high frequency voltage carrier signal is superimposed on the fundamental excitation. This injected signal interacts with the machine saliency and causes phase or amplitude modulation in the resulting current response. The modulated response signal is processed to extract rotor position information.

The carrier can be a rotating vector, alternating vector or inherent high frequency component of pulse width modulator. The carrier is usually injected in d-q components. When an external carrier is injected along d-q component [3], the response to this signal interacts with current controller and system performance is affected.

In this paper, the inherent high frequency zero-sequence component produced by space vector modulation is used as carrier. The response to zero sequence voltage is evaluated from αβ currents are used to obtain rotor position. The carrier frequency will be the same as switching frequency. This method provides higher sensitivity. The signal processing involved for position estimation is simple. For improved speed estimation, a phase- locked loop observer is proposed. This provides fast decay of position error to zero and eliminating additional filters.

2 HIGH FREQUENCY MODEL OF PMSM

Consider the model of PMSM in stationary reference frame αβ0. For high frequency analysis, a reduced model is adopted by neglecting fundamental frequency terms. Also the high frequency resistive voltage drop is neglected. Thus, the voltage equation can be written as follows:

$$u = L\frac{di}{dt} \tag{1}$$

where L is the inductance matrix and $u = \begin{bmatrix} u_\alpha & u_\beta & u_0 \end{bmatrix}^T$

and $i = \begin{bmatrix} i_\alpha & i_\beta & i_0 \end{bmatrix}^T$ are the voltage and current vectors respectively.

In surface mounted PMSM, magnetic saliency is produced by the saturation effect of the stator core, due to the permanent magnet flux. The inductance matrix can be obtained as function of rotor position.

$$L = \begin{bmatrix} L_a - L_b\cos(2\theta) & -L_b\sin(2\theta) & L_b\cos(2\theta) \\ -L_b\sin(2\theta) & L_a + L_b\cos(2\theta) & -L_b\sin(2\theta) \\ \frac{1}{2}L_b\cos(2\theta) & -\frac{1}{2}L_b\sin(2\theta) & \frac{1}{4}L_a \end{bmatrix} \tag{2}$$

where La and Lb are functions d-axis inductance, Ld and q-axis inductance, Lq.

$$L_a = \frac{1}{2}\left(L_d + L_q\right) \tag{3}$$

$$L_b = \frac{1}{2}\left(L_q - L_d\right) \tag{4}$$

La is the average inductance and Lb defines inductance fluctuation.

The current can be solved from (1), as follows

$$\frac{di}{dt} = L^{-1}u \tag{5}$$

For motors with low saliency i.e., Lb << La, the inverse inductance matrix can be approximated as,

$$L^{-1} = \frac{1}{L_a^2}\begin{bmatrix} L_a + L_b\cos(2\theta) & L_b\sin(2\theta) & -4L_b\cos(2\theta) \\ L_b\sin(2\theta) & L_a - L_b\cos(2\theta) & 4L_b\sin(2\theta) \\ -2L_b\cos(2\theta) & 2L_b\sin(2\theta) & 4L_a \end{bmatrix} \tag{6}$$

When zero-sequence voltage is applied, the upper right sub-matrix is considered and the position dependent terms have higher amplitude of 4Lb. Thus by applying a zero sequence carrier we obtain a position dependent signals which is four times higher than injecting a non-zero sequence carrier.

3 FIELD ORIENTED CONTROL

Field oriented control of PMSM is one important variation of vector control methods. With the information of the stator currents and the rotor angle a FOC technique can control the motor torque and the flux in a very effective way. The main advantages of this technique are the fast response and the little torque ripple.

The implementation of this technique will be carried out using two current regulators, one for the direct-axis component and another for the quadrature-axis component, and one speed regulator [4].

Three phase stator currents are transformed into d-q coordinates using Clarke and Park transformation. These currents are used as feedback for the current control loop. Clarke transformation:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{7}$$

Park transformation:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{8}$$
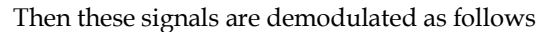
In the outer speed loop, the reference speed is compared with the measured speed and the error signal is fed to the speed PI controller as shown in Fig. 1. The output is the torque command which is proportional to the q-axis current. The error between reference currents, iqref and idref , and measured currents, iq and id are fed to PI controllers to obtain phase voltage, Vqref and Vdref along q-axis and d-axis respectively. The phase voltages are converted to α-β coordinate system using inverse Park transformation.
Inverse Park transformation:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{9}$$

There are many torque control strategies and the goal for all of them is to maintain a linear control over the torque[5]. One of the easiest strategies and most widely used in the industry is Constant Torque Angle (CTA) control. The torque angle is defined as the angle between the q-axis current and the rotor permanent flux. This angle is maintained at 90^0 in this control strategy. For this d-axis current is maintained at zero, so the torque depends only on the amplitude of q-axis current. The main advantage of this control strategy is that it

simplifies the torque control mechanism.

Fig. 1: Block diagram of field oriented control

4 ROTOR POSITION AND SPEED ESTIMATION

In general, high frequency signal injection based sensorless control methods include 3 steps:
1. Signal injection
2. Demodulation process
3. Speed and position estimation

2.1 Rotor Position estimation

Estimation of rotor position is performed by applying a voltage carrier in the zero sequence and evaluating the current response in the α and β components[6].

The voltage signal is injected along zero sequence component when voltage along α and β components are zero. The high frequency zero sequence voltage is naturally generated by an inverter, when controlled with space vector pulse width modulation (PWM). For this, the neutral point of the motor is connected to the midpoint of dc link capacitor through a filter. The carrier frequency is same as switching frequency.

To obtain rotor information the current response is sampled at instants t = (1/2)kTs , where Ts is the swiching period and k = 0,1,...etc. The current response along α and β components at the sampling instant is zero. The voltage equation at sampling instants is given by

$$u_k = \left[0, 0, u_p(-1)^k\right]^T \tag{10}$$

where up is the amplitude of zero- sequence voltage.

By substituting (10) in (5), we obtain current derivative as

$$i_{\alpha,difk} = l_{13}u_pT_s(-1)^k \tag{11}$$

$$i_{\beta,difk} = l_{23}u_pT_s(-1)^k \tag{12}$$

where lij are scalar components of inverse inductance matrix given in (6).

Then these signals are demodulated as follows

$$i_{\alpha,demk} = i_{\alpha,difk}(-1)^k \tag{13}$$

$$i_{\beta,demk} = i_{\beta,difk}(-1)^k \tag{14}$$

The demodulated current is obtained as

$$i_{\alpha,demk} = l_{13}u_pT_s \tag{15}$$

$$i_{\beta,demk} = l_{23}u_pT_s \tag{16}$$

By substituting values for the l13 and l23 from the inductance matrix (6), we get demodulated currents as function of sine and cosine terms.

$$i_{\alpha,demk} = -r_p\cos(2\theta)u_pT_s \tag{17}$$

$$i_{\beta,demk} = r_p\sin(2\theta)u_pT_s \tag{18}$$

where $r_p = 4L_b/L_a^2$.

By using atan2 function, we obtain double the rotor position.

$$2\theta_k = a\tan 2\left(i_{\beta,demk}, -i_{\alpha,demk}\right) \tag{19}$$

The angle obtained after limiting within π radians is divided by two to achieve the electrical rotor position. A combination of high pass filter and low pass filter is used for filtering of demodulated current. The estimated angle is used for reference frame transformation and also for estimating motor speed.

The block diagram of the sensorless control scheme is shown in Fig. 2. The basic drive of the PM synchronous motor is based on field oriented control. The neutral of the motor is connected to midpoint of dc link capacitor through an LC filter in order to inject the carrier. The demodulated and filtered signal is fed to atan2 function. After unwrapping and dividing by two the electrical angle is obtained.
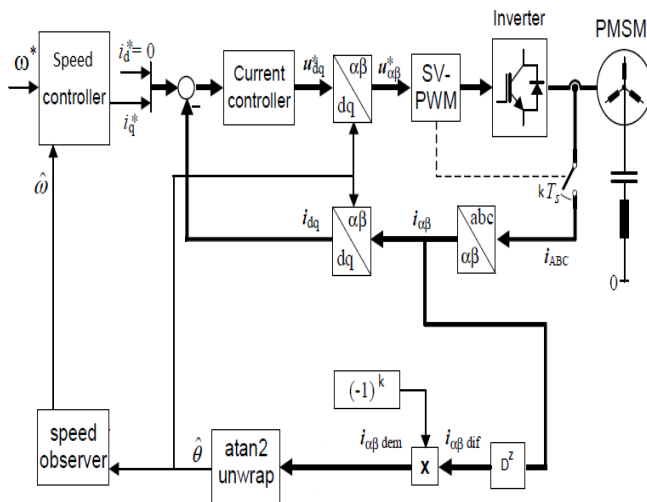
Fig. 2. Block diagram of sensorless control of a PMSM drive

4.2 Improved Speed Estimation

In order to estimate speed from rotor position, usually rotor angle is differentiated. But this would result in noise disturbance. Another approach to estimate speed is done using a speed observer using motor mechanical parameters. Here we use a non linear observer which operates similar to a phase-locked loop (PLL) for further refining of position and estimation of speed.

A PLL is a device which locks an output signal phase relative to an input reference signal phase. PLL observer finds wide application in industrial servo drives [7].Here, the error between the rotor position obtained by atan2 function and estimated position is fed to PI controller.

The error signal can be given by,

$$\varepsilon = \sin[m(\hat{\theta} - \theta^*)] \qquad (20)$$

where m=2 for saliency based position estimation methods.

For small errors, $\Delta\theta = \hat{\theta} - \theta^* \cong 0$,
$$\sin\Delta\theta = \Delta\theta$$

The output of the PI controller is the estimated speed. The speed is integrated to obtain rotor position.

$$\omega^* = \left(k_p + \frac{k_i}{s}\right)\varepsilon \qquad (21)$$

$$\theta^* = \frac{\omega^*}{s} \qquad (22)$$

The estimated speed is used as feedback for the speed controller of the drive system. By using PLL, proper tracking of actual rotor position by the estimated position is obtained.
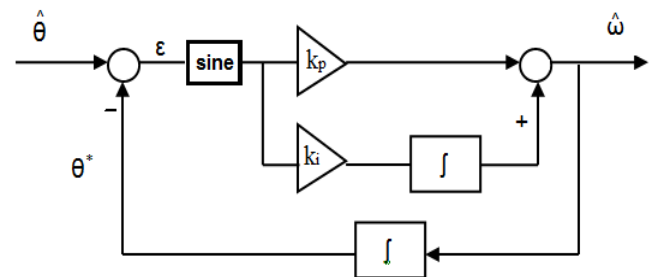

Fig. 3. The proposed PLL observer

5 SIMULATION RESULTS

The simulation of above mentioned sensorless control technique is done using software tool PSIM. The parameters of PMSM used for simulation is given in Table 1.

Table 1: Motor Parameters

Stator Resistance, Rs	2.875Ω
d-axis inductance, Ld	8.5mH
q-axis inductance, Lq	10.34mH
Poles, P	8
Moment of inertia, J	0.0008kgm2
Friction coefficient, B	0.001Nms

The whole system is composed of the controller block, the motor block, the inverter and the reference frame transformation blocks. The switching frequency of inverter is 5 kHz.

Motor is run at reference speed of 350 rpm. The load torque is given as 1Nm. Fig. 4 shows that the estimated rotor position follows the actual rotor position with a time delay. Fig. 5 shows that estimated speed is in agreement with the actual motor speed.

The PI controller value in PLL observer is taken as Kp=310 and Ki = 3. Fig. 6 shows that PLL output position exactly tracks the PLL input position.
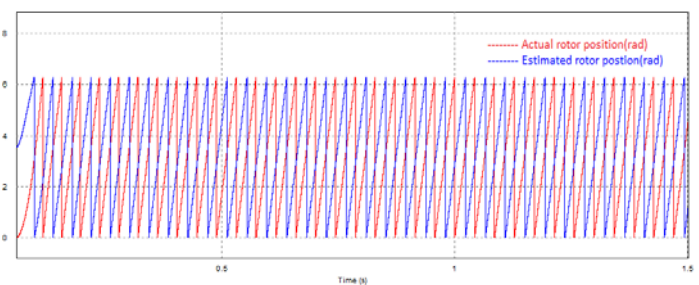

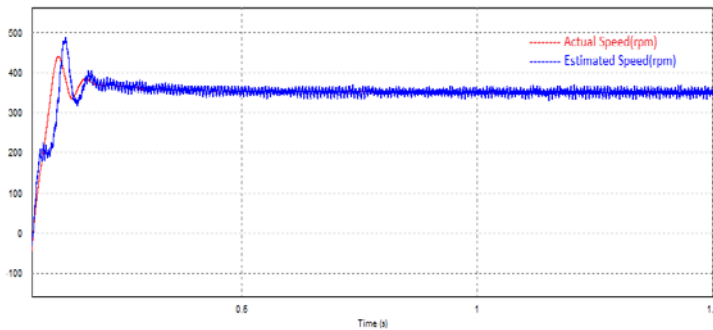Fig. 4. Waveform of rotor position in radians
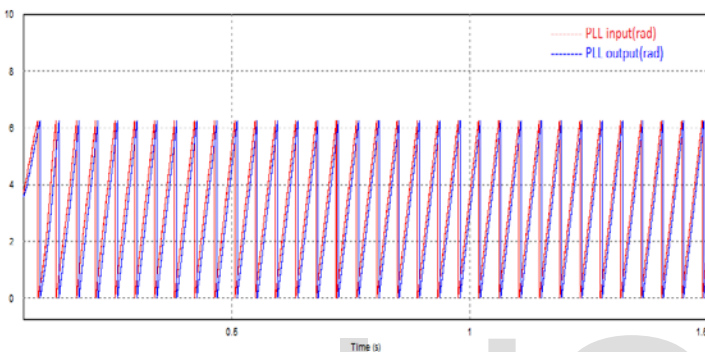
Fig. 5. Speed waveform of motor

Fig. 6. Waveform of PLL input and PLL output

6 CONCLUSION

In this paper, a sensorless control method using carrier injection is discussed. The zero-sequence component produced by space vector PWM is used as carrier. Since zero-sequence excitation is used here, it does not interact with current controller and thus reduce torque pulsation. Also, with carrier frequency same as switching frequency, there are no additional noise produced and system is highly sensitive. A PLL observer is used to estimate motor speed. It provides a filtered position and fast settling of motor speed. This is validated using simulation results.

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