PMSM Angle Detection Based on the Edge Field Measurements by Hall Sensors

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Abstract

This paper presents a two Hall sensor method for rotor angle detection in permanent magnet synchronous motors (PMSM). To minimize the implementation complexity, the system is designed to measure the edge field of permanent magnet pieces. However, there are nonlinearities in the measured values of the edge field. In this work, an angle correction algorithm is proposed, and the improvements in accuracy are verified through experiments. Finally, a field orientation controller is constructed with the proposed angle detection algorithm.

Key Words: Encoderless control, Linear Hall sensor, PMSM

I. INTRODUCTION

Rotor position (angle) information is indispensable for the vector control of permanent magnet synchronous motors (PMSM). To obtain the position information, encoders or resolvers are normally utilized. However, the installation of such devices requires precise machining and coupling devices such as bellows and leaf springs. In some household equipment such as refrigerators, air conditioners, etc., the cost pressure prohibits the use of encoders or resolvers. Further, there could be some noise problems associated with encoder cabling. These problems motivate developments of sensorless algorithms [4]. However, emf-based sensorless algorithms have a generic problem in the low speed region, since the angle observability collapses as the speed approaches to zero [1]-[4]. In practice, it is very difficult to achieve a stable speed response with loads under 0.05pu [3]. An alternative method is a signal injection based sensorless control [5], [6]. This method works at zero speed, but it is not applicable for PMSMs without saliency and costs use of a sizable probing voltage vector.

Significant research effort has been focussed on utilizing Hall sensors for position sensing due to the low cost and the installation convenience of not requiring any mechanical connection to the shaft [7]-[12]. Brushless DC motors (BLDCMs) are the typical examples that utilize discrete Hall sensors for rotor position detection [9], [11]. The Hall sensors monitor the rotor flux, and produce three phase square waves which are 120 degrees apart. These signals are used for the square wave current commutation. Unfortunately, discrete-type Hall sensors yield very rough position information, (60° resolution), so that

they cannot be used for sinusoidal excitation of the current. Interpolation algorithms were developed for the sinusoidal current drive as a way to overcome the low resolution problem. Morimoto et al. [7] utilized a quadratic time-function for interpolating the position data. Capponi et al. [8] employed a mechanical model along with a PID controller to produce intermediate position estimates. Ozturk et al. [9] utilized an acceleration estimate for the rotor angle interpolation, and applied to the direct torque control of a washing machine. In many cases, Hall sensors are positioned near the stator side to sense the radial component of the rotor flux. However, due to the armature reaction, air gap field is affected significantly by the stator current flow, leading to erroneous position monitoring [10]. Also, the physical positioning randomness (variation) of Hall sensors may generate significant errors at high speeds when the vibration is large. The resultant rotor position measurement errors cause reduction in the maximum torque and speed jitter especially in the high-speed field weakening region [13]. Samoylenko et al. [11] showed that misplaced Hall sensors led to a unbalanced operation of the inverter and motor, causing low-frequency harmonics in torque. They proposed several average-filtering techniques to mitigate the unbalanced effects. Chi et al. [13] utilized a sliding mode observer in obtaining a current estimate and finally a rotor angle estimate. They claimed that the control scheme featured high torque production and fast dynamic response, especially in the wide field weakening high-speed range. Hall sensors were utilized for mover position sensing in permanent magnet linear synchronous motors [14], [15]. Chang and Tzou [16] used three linear Hall sensors in estimating the position and speed of a PMSM.

In this work, two Hall sensors are utilized for rotor position detection in a PMSM. However, the main difference from the previous works is that linear type Hall sensors are employed

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Fig. 1. Cross sectional (a) and longitudinal (b) views of the PMSM used for experiments.

to detect the rotor permanent magnet (PM) edge field. Specifically, Hall sensors are positioned at one side of the rotor to detect the PM edge field in the axial direction. The sensed edge field signals are used for rotor angle estimation, but the angle estimation contains a nonlinearity caused mainly by strong third order harmonics. To correct the angle error, a nonlinear correction algorithm is proposed.

II. ROTOR PM EDGE FIELD MEASUREMENTS

The purpose of this work is to develop a rotor position measuring device, and an algorithm for a PMSM that enables the field oriented control. we do not attempt to measure the radial air gap field, since the airgap field is so high ($> 0.7T$) in the radial direction that Hall sensors are easily saturated. Note that the general measuring range of linear Hall sensors is $(-1000, 1000)$ gauss. Fig. 1 (a) shows a cross sectional representation of the motor used in this experiment. It is a 10kW, four pole interior PMSM. Each rotor pole is comprised of two PM's. Two Hall sensors are mounted to sense the z -directional field component. Note that the two Hall sensors are positioned 45° apart. Fig. 1 (b) shows a side representation of the motor showing how a Hall sensor detects the z -directional

edge field of a PM. The Hall sensors are soldered to a circular PCB board with some filtering circuits, and the distance to the PM is 7mm.

III. NONLINEARITY CORRECTION ALGORITHM

Since the two Hall sensors are positioned 45° apart, the two measured signals, x_a and x_b are shifted 90° from each other as shown in Fig. 2 (a). That is, x_a and x_b are supposed to produce sine and cosine signals, and the rotor electrical angle estimate, $\hat{\theta}_e$ will be calculated according to $\hat{\theta}_e = \tan^{-1} \left(\frac{x_a}{x_b} \right)$. Fig. 2 (b) shows an $x-y$ plot of x_b and x_a . The shape should be a circle, if they are perfect cosine and sine waves. But, due to the nonlinearity of the z -directional edge field, the signals contain a significant amount of harmonics. Specifically, the peak values are flattened. As a result, the $x-y$ plot looks like a rounded square. Fig. 2 (c) shows the angle estimates, $\hat{\theta}_e$ versus the real angle values, θ_e measured by an encoder. This also shows that there are significant angle errors. The error has a special pattern: Observing Fig. 2 (b), errors are large in neighborhoods of $\hat{\theta} = 0^\circ, 90^\circ, 180^\circ, 270^\circ$, whereas errors are small in neighborhoods of $\hat{\theta} = 45^\circ, 135^\circ, 225^\circ, 315^\circ$. Fig. 3 displays the Hall sensor signal spectrum. Note that the third

Fig. 2. Hall sensor signals and rotor position estimates: (a) Hall sensor signals, x_a and x_b versus θ_e , (b) x-y plot of x_a and x_b , and (c) $\hat{\theta}_e$ versus θ_e .

Fig. 3. The spectrum of Hall sensor signal.

order harmonic can not be eliminated by a linear filter, since the frequency changes as the motor speed varies. But, a simple correction guide line is

- i) x component should be increased in $-45^\circ < \hat{\theta} < 45^\circ$ and $135^\circ < \hat{\theta} < 225^\circ$.
- ii) y component should be increased in $45^\circ < \hat{\theta} < 135^\circ$ and $225^\circ < \hat{\theta} < 315^\circ$.

Thus, we partitioned the x, y plane into four sectors as shown in Fig. 4. In each sector, either x_a or x_b is corrected by adding or subtracting $k||x_a| - |x_b||$, where k is a constant. The proposed signal correction algorithm is summarized as

$$\text{Sector I} \quad \begin{cases} \tilde{x}_a = x_a, \\ \tilde{x}_b = x_b + k||x_a| - |x_b|| \end{cases} \quad (1)$$

$$\text{Sector II} \quad \begin{cases} \tilde{x}_a = x_a + k||x_a| - |x_b||, \\ \tilde{x}_b = x_b \end{cases} \quad (2)$$

$$\text{Sector III} \quad \begin{cases} \tilde{x}_a = x_a, \\ \tilde{x}_b = x_b - k||x_a| - |x_b|| \end{cases} \quad (3)$$

$$\text{Sector IV} \quad \begin{cases} \tilde{x}_a = x_a - k||x_a| - |x_b||, \\ \tilde{x}_b = x_b \end{cases} \quad (4)$$

Therefore, no correction is made at $\hat{\theta} = 45^\circ, 135^\circ, 225^\circ, 315^\circ$, while the maximum corrections are made at $\hat{\theta} = 0^\circ, 90^\circ, 180^\circ, 270^\circ$. In between, the correction term is linearly proportional to the difference between the magnitudes of x and y components. A nonlinear

Fig. 4. The proposed nonlinearity correction algorithm.

function could be used for better correction. For simplicity, however, just a linear function with parameter, k is utilized. The correction method is shown schematically in Fig. 4. Fig. 5(a) shows the plots of corrected signals with $k = 0.3$. The corrected signals are denoted by $\tilde{x}_a$ and $\tilde{x}_b$. Compared with the plots shown in Fig. 2, they look closer to sine and cosine waves, and the corresponding $x-y$ plot looks closer to a circle. The same correction was repeated for different k 's. Fig. 5(b) and 5(c) show the plots of corrected signals when $k = 0.4$ and 0.5 , respectively. It looks like over-corrections were made in both cases, since the $x-y$ plot turned out to be a diamond shape. However, the maximum angle error was decreased gradually by increasing k . Specifically, the maximum errors were $7^\circ, 6^\circ$, and 5° for $k = 0.3, 0.4$, and 0.5 , respectively. To see the improvements from the harmonic view point, FFTs were taken on x_a and $\tilde{x}_a$. Fig. 6 (a) shows the maximum angle error (in degrees) which decreases as k increases. Fig. 6 (b) shows the normalized harmonics by the fundamental component. Note that the third order harmonics decrease steadily as k increases. But the fifth order harmonics increase, and are greater than the third order harmonics when $k = 0.5$. Thus, we chose $k = 0.5$ in this experiment.

IV. CONTROL BLOCK DIAGRAM AND EXPERIMENTAL SETUP

Fig. 7 shows a field oriented control block diagram based on the proposed angle detection algorithm. Hall sensor signals are

Fig. 5. Corrected signals, $\tilde{x}_b$ and $\tilde{x}_a$, x-y plot of them and estimated angles, $\hat{\theta}_{ec}$ by the nonlinearity correction algorithm : (a) $k = 0.3$, (b) $k = 0.4$ and $k = 0.5$.

Fig. 6. Maximum angle error (a) and FFT's of corrected signals ($\tilde{x}_a$) (b) for different k 's.

filtered through analog low pass filters before being fed into the A/D converter of the DSP. The converted data are corrected by the proposed nonlinear correction algorithm (1)-(4). Finally, the rotor position estimate is calculated by

$$\hat{\theta}_{ec} = \arctan\left(\frac{\tilde{x}_a}{\tilde{x}_b}\right). \quad (5)$$

Fig. 7. Field oriented control scheme with the angle estimation algorithm.

The field oriented control, as well as the position detection algorithm, were implemented in a DSP board (TMS320F2812) along with an inverter program. Fig. 8 shows pictures of a Hall sensor board and a motor end. The measurement range of the linear Hall sensors (A1322: Allegro Microsystems Inc.) is $(-800, 800)$ gauss. The parameters of the PMSM and the inverter used in these experiments are summarized in Table I.

V. EXPERIMENTAL RESULTS

Fig. 9 (a) and (b) show the rotor angle estimates before and after the nonlinear correction at a low speed (10 rpm) and high speed (6000 rpm), respectively. In both cases, accuracy improvements are observed with the proposed scheme. The

Fig. 8. Hall sensor board and its assembled view: (a) Hall sensor board and (b) assembled view at an end of the motor.

TABLE I
MOTOR AND INVERTER PARAMETERS

Parameters	Values
DC-link voltage	300 V
Switching frequency	8 kHz
Rated power	10 kW
Rated current	60 A
No. of poles	4 poles
No. of slots	36 slots
Rated speed	6000 rpm
D-axis inductance (L_d)	0.063mH
Q-axis inductance (L_q)	0.78mH

maximum angle error was reduced to $\pm 6^\circ$ in the electrical angle ($\pm 3^\circ$ in mechanical angle) from $\pm 11^\circ$.

Fig. 10 and 11 demonstrate the speed control performance. The full load (16Nm) was applied to the PMSM at high speed

(a)

(b)

Fig. 9. Angle estimates and the errors before and after the nonlinearity correction (before : $\hat{\theta}_e$, e_{before} , after : $\hat{\theta}_{ec}$, e_{after}) : (a) 10rpm, (b) 6000rpm.

Fig. 10. Speed control performance and angle estimation error at 10 rpm with full load (16 Nm).

(a)

(b)

Fig. 11. (a) Speed control performance and angle estimation error at 3000 rpm with full load (16 Nm) and (b) a magnified plot of region A.

(3000 rpm) and low speed (10 rpm). In both cases, the speed was well regulated, however, the angle error became larger when the load was applied. The reason is the stator flux influences the edge field to some extent and induces the phase delay in hall sensor signals. However, this problem does not make the PMSM unstable because the angle error converges to a constant value.

From these results, the rotor angle detection device using the Hall sensors can be used for the whole speed range and shows the good speed regulation performance against the load variation.

VI. CONCLUSION

A rotor position detection method was developed by utilizing two linear Hall sensors which were displaced by 90 degrees of electrical angle. The proposed method does not require any moving parts nor an extension of the permanent magnets. However, the sensed edge fields contain large third order harmonics. The proposed correction algorithm was devised to correct the rotor angle estimation error caused by the nonlinearity. The proposed algorithm is simple to use, and its effectiveness was demonstrated with the field oriented control. Thus, the proposed method is suitable for applications where a precise control is not essential, such as blowers, pumps, and cranes.

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