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Application of Hall Position Sensor in Control and Position Estimation of PMSM- A Review

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Abstract—This paper reviews the use of permanent magnet synchronous motors (PMSMs) across industries and the significance of precise rotor position and motor speed data. It presents two methods of obtaining rotor position information: using mechanical position sensors, which are expensive and less reliable, and the rotor position observer method, which is sensitive to changes in motor parameters. This paper reviews the advantages, drawbacks, challenges, and applications of low-resolution Hall position sensors for PMSM position estimation and control, in order to balance performance and cost. It also discusses recent solutions to address issues related to misplaced Hall sensors and fault-tolerant control, while looking forward to future developments in this area.

Index Terms—Permanent magnet synchronous motor (PMSM), Hall position sensor, Rotor position estimation, Hall sensor misplacement, Fault-tolerant Control.

I. INTRODUCTION

The increasing popularity of hybrid and electric vehicles has made permanent magnet motors more popular in the automotive industry. These motors offer high power density, ease of maintenance, efficiency, and reliable dynamic performance. Brushless DC (BLDC) motors are generally controlled by Hall-effect sensors with a 60-degree electrical angle resolution when used with low-resolution position sensors [1], [2].

In many applications, rotor position and speed acquisition are critical to high-performance PMSM control. In terms of position-measuring methods, the control systems of PMSMs can be divided into two major categories. The first type involves using high-precision mechanical position sensors to determine motor speed and rotor position, such as resolvers and photoelectric encoders [3]. Although these methods provide precise control of the motor, they result in larger volumes and more costs, and they are easily restricted by the room condition. In addition, as the mechanical position sensors may fail during the motor operation, their reliability is an issue.

Alternatively, rotor position and motor speed can be measured without using a sensor, such as using the rotor position observer methods [4], using high-frequency signal injection methods [5], or using Kalman filter (KF) approaches [6]. These methods are sensitive to motor parameter variation, temperature, and non-linear characteristics of inverters. Consequently,

it is difficult to estimate speed and position accurately over large speed range applications based on these methods [7].

Due to its low cost and the ability to provide certain speed and rotor position information, the low-resolution Hall position sensor has become the ideal choice to balance performance and cost [8]–[11].

Many investigations have been conducted on PMSM drives using Hall sensors in recent years [11]–[13]. In [11], different rotor position and motor speed estimation methods using Hall position sensors were reviewed. Various torque measurement and estimation methods for PMSMs have been compared with Hall-sensor-based approaches in regard to cost, sensitivity to parameter variations, computational time, accuracy, and robustness in [14]. An investigation of implementation issues of PMSM control methods with Hall position sensors is presented in [15].

The purpose of this paper is to review the application of Hall position sensors for PMSM drive applications. The paper is organized as follows: in section II the working principle of Hall-based position sensing and how misplaced Hall sensors may result in adverse consequences is discussed. In Section III, different estimation methods for rotor position and speed will be presented. Section IV discusses future trends and recent studies, such as fault-tolerant control of PMSMs using Hall position sensors. Conclusion is given in Section V.

II. ANALYSIS OF HALL POSITION SENSOR SIGNALS

A. Working principle of Hall-based position sensing

Figure 1(a) shows the position of three-phase Hall sensor's installation for a one-pole PMSM. $Hall_A$, $Hall_B$, and $Hall_C$ are three-phase position Hall sensors. When a rotor rotates, the Hall position sensor produces a rectangular wave with a variable frequency. During one cycle of the rotor, three rectangular waves are generated with a phase difference of 120° electrical angle and 180° pulse width. There are six Hall sections with 60° electrical angles for each cycle of 360° electrical angles. Each section corresponds to one state of the three-phase Hall signal. Fig. 1(b) shows this relation between the phase Hall signal and the back electromotive force (back-EMF) [13]. In order to control the PMSM in the desired way, it is required to obtain the continuous position information of the motor rotor based on the motor Hall signals.

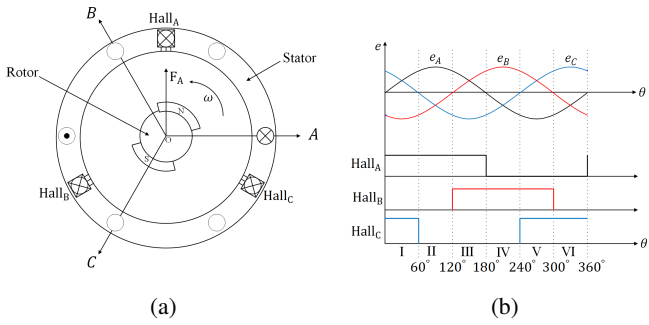


Fig. 1. (a) The Hall position sensors for a one-pole PMSM. (b) Correspondence diagram of Hall position signals and motor back-EMF voltages.

B. Consequences of misplacement of Hall sensors

Fig. 2 depicts an incorrect installation of the Hall position sensors. The misplacement of Hall sensors will result in three unequal misplacement angles namely ψ_a , ψ_b , and ψ_c , which corresponds to the three phases of the PMSM, respectively. Hence, the imprecise position of the Hall sensors distorts the estimation of the rotor position. In order to avoid harmonic currents, an algorithm is needed to mitigate this distortion. This will also result in low-frequency torque ripples, noise, and vibrations in the PMSM performance [16].

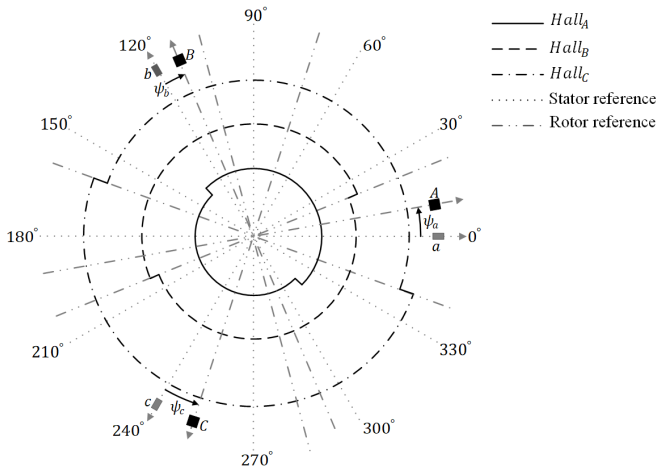


Fig. 2. Diagram of misplaced Hall sensors signals for PMSM resulting in three unequal misplacement angles [16].

Several researches have been done to deal with issues resulted by misplacement of Hall position sensors in PMSMs such as in [17], where a phase-locked loop (PLL) enhances the transient response of PMSM with Hall sensor-based control. However, the observer design is complex and highly dependent on the motor parameters.

III. ESTIMATION METHODS OF MOTOR SPEED AND ROTOR POSITION

It is also noted in [11] that there are generally three different methods for estimating speed and position based on Hall

position sensors, namely the interpolation method [18], the observer method [19] and the filter method [20], which will be discussed in more detail in this section. Despite the fact that the interpolation and filter methods are easy to implement, they result in the phase lag and noise in a closed-loop speed control system that prevent high-performance in many PMSM applications. It is possible to estimate the position and speed of the rotor more precisely with the observer method based on the model parameters of the motor system. It should be noted, however, that the observer method is sensitive to motor parameters [11]. Several nonlinear position control algorithms have been introduced for the purpose of increasing standstill stability [21], [22].

A. Interpolation method

The interpolation method employs a discrete function approximation to estimate rotor speed and position. The entire rotating space is divided into six sectors based on the states of the Hall signals. The continuous rotor position information is calculated using the interpolation method, assuming the rotor speed within a sector is constant [18], [23].

As presented in [11], among the Hall signal interpolation methods, the following method are the most commonly used:

- the average speed method,
- the average acceleration method,
- and the least square method.

The average speed method can be used to estimate the position of the rotor in the next Hall sector based on the average velocity in the last Hall sector. Due to the lower electrical time constant of the motor than its mechanical time constant, the speed of each sector is assumed to be constant regardless of speed variations between sectors. The average speed estimation is restricted by the deviation of the Hall installation location. Therefore, the motor speed obtained from it fluctuates greatly, which affects the estimation of the rotor position.

Hence, a motor acceleration and moving average interpolation methods have been introduced to deal with this issue. The average acceleration method assumes that the angular acceleration in each Hall sector is constant, and it does not change abruptly when the sector is switched [24], [25]. The speed and position estimation from Hall sensors signals based on moving average method is shown in Fig. 3 and can be calculated by:

$$\begin{cases} \bar{a}(t_i) = \frac{\hat{\Omega}(t_i) - \hat{\Omega}(t_{i-1})}{T_{Hall}(t_i)} \\ \hat{\Omega}(t_{i,k}) = \hat{\Omega}(t_i) + \bar{a}(t_i) \cdot (t_{i,k} - t_i) \\ \hat{\theta}_0(t_{i,k}) = \hat{\theta}_0(t_i) + \hat{\Omega}(t_i) \cdot (t_{i,k} - t_i) + \frac{1}{2} \bar{a}(t_i) \cdot (t_{i,k} - t_i)^2, \end{cases} \quad (1)$$

where $\bar{a}(t_i)$ is the average acceleration at moment t_i and $\hat{\theta}_0(t_{i,k})$ represents the position estimate at Hall commutation moment t_i .

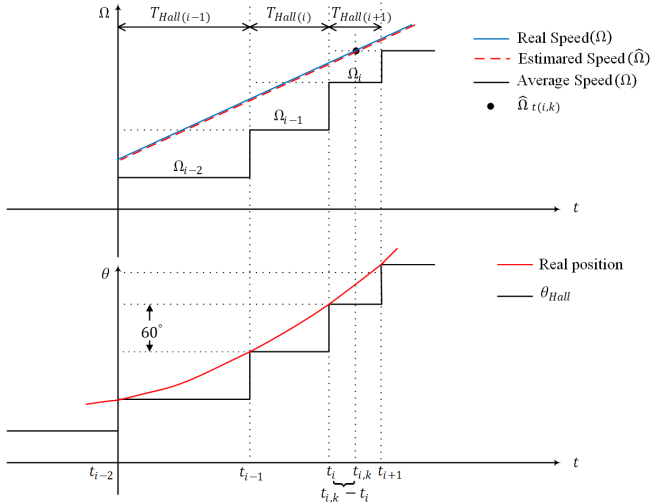


Fig. 3. Speed and position estimation from Hall sensors signals based on moving average method [25].

When the speed fluctuates greatly, the average acceleration method can cause rotor pulsation. This can negatively impact normal motor operation. However, when the speed fluctuates greatly, the system error can be ignored. This method is particularly not suitable in applications with high dynamic performance requirements. As a result of the Taylor series expansion order, the estimation error will be reduced. However, the difficulty of software implementation increases accordingly, resulting in significant lags in the estimation result [26].

The least squares method considers the influence of the mechanical installation error of Hall position sensor on the angle correction [27]. A least-squares method is used for correcting the effect of the misplaced Hall sensors in [28] by using second-order Taylor linear interpolation. It is proposed in [29], to combine non-model-based least square algorithms with model-based sliding mode observers (SMOs) for estimating position and speed, as illustrated in Fig. 4.

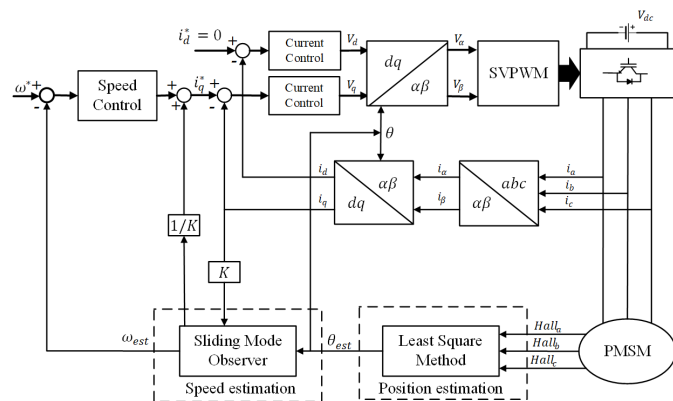


Fig. 4. The control block diagram of PMSM based on combining least square algorithm and SMO method [29].

B. Filter method

Since the filter method does not require a function that is based on the motion equation of the PMSM, it has been introduced instead of interpolation. Coordinate transformations are used in this method to transform Hall signals into a Hall rotation vector containing information about the rotor position. It is possible to consider discrete signals as the superposition of sine wave signals via Fourier decomposition. Filtering is used to extract fundamental signals from Hall vectors obtained from coordinate transformations [30], [31].

In [20], an improved orthogonal PLL is proposed that reduces speed ripple. Among its main advantages are the small position error and the dynamic performance. Variable electrical frequency poses significant drawbacks such as the variation of the low-pass filter cutoff frequency and the need to adjust adaptive controller parameters. Hall sensors installation error in filter method control of PMSM is analyzed in [32]. In this reference, the fundamental signals are extracted via synchronous frequency tracking filters (SFTF) as shown in Fig. 5.

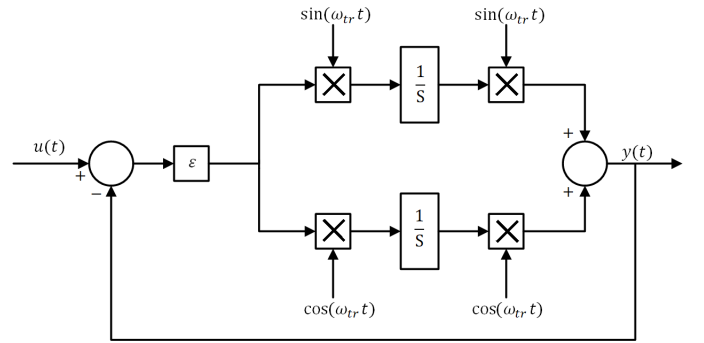


Fig. 5. Block diagram of SFTF [32].

A deadbeat predictive current control method was developed to improve the accuracy of the estimation of rotor speed and position with Hall position sensors. The output signals from Hall sensors are transformed by Clark transformation into Hall vectors containing high-order harmonics. In order to extract the fundamental waves of the Hall vector, an adaptive vectorial filter (AVF) is introduced. An improved PLL structure estimates the rotor speed and position from fundamental waves [33].

C. Observer method

Implementation of the previous methods, based on signal processing, is relatively straightforward. There is, however, the problem of time delay and an increase in speed estimation that cannot be avoided, resulting in slower, inefficient, and sometimes even unstable motions. There are other solutions, such as state observers [19], [34], [35], and Kalman filters [36], which are model-based technologies that require information about the motor. In [30], the Luenberger state observers based on the motor's mechanical parameters were introduced.

As proposed in [37], rotor position estimation can be obtained using a back-EMF observer combining low-resolution

Hall position signals. Unlike conventional speed observers, the back-EMF speed observer uses no external parameters such as the moment of inertia, which eliminates the problem caused by the moment of inertia error in influencing estimation accuracy. Therefore, it has good robustness to mechanical parameters and is insensitive to the moment of inertia and actual torque. However, it is difficult to fully determine the real rotor position at low speed applications because the amplitude and frequency of the back-EMF voltages are relatively low. In addition, the observer is greatly affected by the current sampling accuracy, and the signal-to-noise ratio, which is relatively low at light load operation [38].

Position vector tracking observer for control of PMSM with the Hall sensor has been proposed in [24]. The position vector tracking observer can not only realize the smooth start of the motor at low speed, but also the observation result is less affected by the installation error of the Hall sensor. However, the parameter setting of the observer system is complicated. Excessively high controller bandwidth can lead to significant fluctuations in the observed instantaneous speed and estimated position. If the bandwidth is set too low, the stability of the observer cannot be guaranteed [39]. A vector tracking observer based on Fourier decoupling feedback of Hall signal is proposed in [40], which decouples the position vector into fundamental and high-order harmonic components. The overall block diagram of the observer with Hall signal feedback decoupling is shown in Fig. 6. Choosing the appropriate expansion terms of the discrete Fourier series is the challenge of this method. While this method can ensure that the motor runs in its full speed range, the problem lies in extending the speed loop bandwidth at low speeds [40], [41].

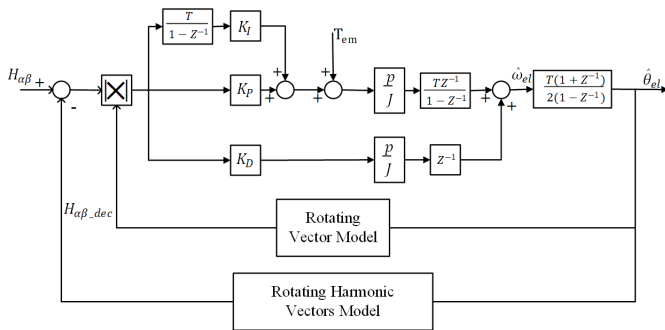


Fig. 6. Block diagram of rotor position estimation of vector tracking observer [40].

In order to improve the accuracy of the estimation and reduce the lag of the rotor speed and position of PMSMs, cascaded observers have been proposed in some articles [42]. A dual observer method is proposed in [43]. This method is composed of two cascaded observers as shown in Fig. 7. The first observer is used to estimate rotation speed, and the second observer is used to estimate rotor position.

Compared to the filter method, this technique uses torque feedforward and exhibits superior frequency characteristics. Cascade observers, unlike feedback decoupling, can estimate

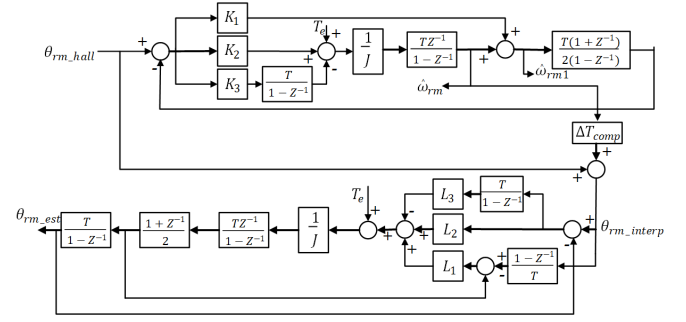


Fig. 7. Control block diagram of cascade observer to estimate speed and rotor position [43].

instantaneous rotor speed and position. However, due to the complex coordination required between the parameters of cascade observers, motor ratings, and control system parameters, its use in current industries is limited [44], [45]. A cascaded Luenberger observer combined by using a feedback decoupling block is proposed in [46] to mitigate the low-order noises resulted by the deviation of Hall position signals as depicted in Fig. 8.

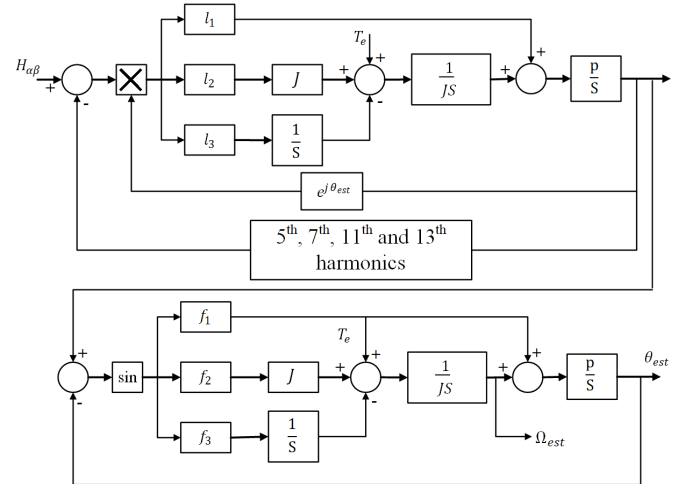


Fig. 8. Cascaded dual Luenberger observer [46].

IV. FUTURE TRENDS

It is critical to note that interpolation and filtering are non-model position and speed estimation methods that can only provide stable motor control within a limited range of speed operation as discussed in [11]. These estimation methods can only be applied in situations where the speed remains relatively constant, such as in fans and water pumps, since these methods include higher frequency harmonic components. As long as the observer method has closed-loop characteristics, it is not affected by the fixed error of Hall sensor installation. Electric vehicles and home appliances have popularized this technique due to its ability to have a balance in accuracy and cost. The main factors to consider when implementing these methods in real microcontrollers, especially when applied to mass-production applications, are cost, required memory, burden

time, speed estimation error during steady state, and transient periods.

For robust dynamic prediction performance across all speed ranges, parameter identification modules can be supplemented by closed-loop observers. To achieve high-performance PMSM control, enhanced speed estimation methods can also be used to minimize system error and estimate rotor position accurately in applications with a wide speed-range operation of the motor.

There are several factors that can damage a Hall sensor, including temperature changes, pollution, vibrations, and strong magnetic fields [47]. A malfunctioning Hall sensor can cause speed fluctuations, position errors, and mechanical system failures. In order to increase the reliability of the position estimation method, fault tolerance methods have been developed using failed Hall position sensors [48], [49]. In [50], a hybrid position observer is proposed for online fault detection and fault tolerant control of PMSM. In order to accomplish this, a fault detection variable based on the three adjacent Hall states is formulated to determine the fault type. Authors in [51] proposed a fault detection scheme for Hall sensors based on the encoded signals of Hall jump edges. A fault-tolerant control switching scheme is designed to detect faults and to make switching possible in the event of a fault. Additionally, the state switching of the controller is used to produce a fault-tolerant control method for Hall sensors. It uses a sensorless scheme based on SMO, which is a fault tolerance mechanism for medium and high speeds. Consequently, it may be useful to consider sensorless control of three-phase PMSM at low speed, sensorless start-up at zero speed, and fault-tolerant control of three-phase PMSM at full speed in various industrial environments [51].

V. CONCLUSION

In this paper, the use of Hall position sensors in PMSM drives is explored. Various methods for estimating rotor position and motor speed, such as the interpolation method, filter method, and observer-based methods, are discussed and reviewed in terms of their benefits, limitations, challenges, and applications. Moreover, recent research has focused on addressing the issues related to incorrect installation of Hall sensors and implementing fault-tolerant control for PMSMs that rely on Hall position sensors.

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