A simple approach to detect and correct signal faults of Hall position sensors for brushless DC motors at steady speed

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Abstract. In order to realize reliable commutation of brushless DC motors (BLDCMs), a simple approach is proposed to detect and correct signal faults of Hall position sensors in this paper. First, the time instant of the next jumping edge for Hall signals is predicted by using prior information of pulse intervals in the last electrical period. Considering the possible errors between the predicted instant and the real one, a confidence interval is set by using the predicted value and a suitable tolerance for the next pulse edge. According to the relationship between the real pulse edge and the confidence interval, Hall signals can be judged and the signal faults can be corrected. Experimental results of a BLDCM at steady speed demonstrate the effectiveness of the approach.

1. Introduction
Brushless DC motors (BLDCMs) have been used in many fields from aerospace, military, industrial to domestic applications owing to their advantages on smaller size, higher efficiency, simpler structure, easier control, and higher performance\cite{1}. Switch-mode Hall position sensors are often mounted in BLDCMs to detect the information of the rotor position and instruct the current commutation. However, the reliability of Hall position sensors together with signal processing and transmission circuits maybe degraded with long-time running in the harsh environment. Once if Hall signals become abnormal due to the faults in Hall position sensors or the signal channels, false commutation will lead to improper running of the motor, even with large peak current which can harm the health of the motor\cite{2}.

For the detection and correction of Hall signal faults in BLDCMs, many research results have been reported in literatures. Ma and Zhou proposed a method to diagnosis and reconstruct Hall signals for doubly salient permanent magnet motor by using the last pulse edge in \cite{3}, but the pulse errors were not taken into account. Fu and his collaborators proposed a linear extrapolation based method to judge Hall signals and reconstruct the faulty signals in \cite{4}, but the mounting errors of Hall sensors were required \textit{a priori}. Tashakori and Ektesabi designed a simple fault tolerant control system for Hall-effect sensors failure of BLDC motors in \cite{5}, but the FFT based failure diagnosis method required large amount calculations and the remedial strategy of failure signals also required the information of the mounting errors of Hall sensors.

The back electromotive force (EMF) method is an alternative to detect and correct faulty Hall signals for BLDCMs without the information of the mounting errors of Hall sensors in \cite{6} and \cite{7}. Since novel measurement information is introduced in \cite{6} and \cite{7}, EMF method can be applied to not
only the detection and correction of the mounting errors of Hall sensors, but also the situation of three breakdown Hall sensors. However, this method may increase the complexity of hardware and can not be used at low speed.

In order to improve the reliability of BLDCMs running at steady speed, this paper proposes a simple approach to detect and correct signal faults of Hall position sensors. This approach only adopts prior information of pulse intervals in the last electrical period and the mounting errors of Hall sensors are not necessary. Compared with other ones, this approach is easy to implement and the other information except for the pulse intervals in the last electrical period is not needed.

2. BLDCM principles and problem description

2.1. BLDCM principles

Figure 1 shows the principles of a BLDCM speed control system commutated by three Hall-effect position sensors and supplied by a DC/DC buck converter plus a three-phase half-bridge converter. Hall position sensors are mounted inside BLDCM with 120° phase difference and can output switch-mode signals representing rotor positions. The buck converter is in charge of regulating the motor current by chopping the supplied voltage, while the half-bridge converter is in charge of commutating the phase currents according to Hall commutation signals. For any time instant, only one phase is energized by turning on the correspondent power switch. If the rising edge of Hall signal for some phase is detected, this phase will be energized after turning off the conducting phase by manipulating correspondent switches, i.e., commutation.

Under ideal conditions, the commutation instant happens at 30° and the conduction mode goes on during the whole 120° constant plateau of EMF for any phase, as shown in Figure 2(a). For any phase in conduction mode, the voltage equation can be written as:

\[ u = Ri_k + Ld_i_k/dt + e_k \]  

(1)

where \( u \), \( R \), and \( L \) denote the chopping voltage, winding resistor, and inductance respectively; \( i_k \) and \( e_k \)
denote the current and EMF of phase $k$ respectively, $k=a,b,c$. If the commutation is accurate, EMF $e_k$ will be its amplitude $E$ in (1) and the desired current can be obtained by current loop. The ideal stator current has rectangular form with width of $120^\circ$. Assume the amplitude of the stator current is $I$, then the electromagnetic torque can be written as:

$$ T_c = \frac{1}{\omega} (e_{ia}i_a + e_{ib}i_b + e_{ic}i_c) = \frac{EI}{\omega} = K_TI \tag{2} $$

where $\omega$ and $K_T$ denote the motor speed and torque coefficient respectively; $K_T=E/\omega$. By using electromagnetic torque in (2), the motor speed can be regulated smoothly according to the dynamical equation as follows:

$$ J \frac{d\omega}{dt} = T_c - D\omega - T_L \tag{3} $$

where $J$, $D$, and $T_L$ denote inertia, damping coefficient, and load torque of the motor respectively.

2.2. Problem description

However, Hall position sensors and signal transmission channels may fail during long-term operations in the harsh environment. As a result, Hall signals used as commutation instructions will become abnormal. For example, the edge of Hall signal may arrive in advance or late. In severe cases, Hall signal may remain high or low all the time [4]. Abnormal Hall signals will lead to improper commutations. Figure 2(b) shows an advanced commutation due to an early rising edge, while Figure 2(c) shows a retarded commutation due to a late rising edge of Hall signal in phase A. Obviously, the EMF $e_k$ in (1) will not be its amplitude $E$, it may be less or far less than $E$. Thus, $(u-e_k)$ will become larger and peak current will arise according to (1). Especially, when $e_k$ is negative during commutation interval, the peak current may be larger than the permitted value and it will endanger the safe operation of the motor.

Therefore, a detection and correction method for Hall signal faults will be proposed to improve reliability of BLDCMs in this paper. Even when the commutation information becomes incomplete owing to the failure in the partial Hall sensors or signal transmission channels, BLDCM still can work properly by using the proposed method.

3. Detection and correction of Hall signal faults

In this section, a simple approach is proposed to detect and correct Hall signal faults. The main idea of the approach is to detect and correct the next edge according to the prior information of Hall signals in the last electrical period. For the next edge of Hall signal, the approach includes three steps: prediction of the time instant, configuration of the confidence interval, and design of detection and correction algorithm.

3.1. Prediction of next edge instant

The core of the detection and correction method is to predict the time instant of the next edge for Hall signals. As we know, the electrical degree between two contiguous pulse edges (rising or falling) of Hall signals should be $60^\circ$ if many kinds of unexpected factors are not taken into account, such as installing errors of Hall sensors, mounting errors of rotor magnetic poles, and delay of processing circuits, etc. However, the electrical degree of adjacent pulse edges will not be $60^\circ$ owing to the effects of the above factors. Even if the stability of the motor speed is high enough, the pulse width of Hall signals will vary at a certain extent. Therefore, the time instant of the next pulse edge can not be predicted by using the width of the last pulse when the effects of the above unexpected factors are taken into account.
If only installing errors of Hall sensors are taken into account, the time instant of the next pulse edge can be predicted by using the prior information of the pulse width in the last electrical period for Hall signals in BLDCMs at steady speed. As shown in Figure 3, the time intervals between contiguous pulse edges (rising or falling) in the last electrical period can be denoted by $\Delta t_1, \Delta t_2, \cdots, \Delta t_6$. If the last edge of the last electrical period is assumed to be the rising edge of phase A at instant $t_k$, then the next edge needs to be detected is the falling edge of phase C. Assume the time instant of the next edge is $t_{k+1}$, then the time interval $\Delta t$ between the rising edge of phase A and the falling edge of phase C needs to be predicted before the prediction of $t_{k+1}$.

Examine the time intervals $\Delta t_1, \Delta t_2, \cdots, \Delta t_6$ in the last electrical period, it can be found that $\Delta t_1$ is the mirror before 360° electrical degree of the time interval $\Delta t$ to be estimated. Even if installing errors of Hall sensors exist, $\Delta t$ equals to $\Delta t_1$ approximately when the stability of the motor speed is high enough. Therefore, the next time interval $\Delta t$ can be estimated as:

$$\hat{\Delta t} = \Delta t_1$$  \hspace{1cm} (4)

In practical engineering, only 6 registers are needed to store 6 time intervals between two contiguous pulse edges in the last electrical period for Hall signals. When estimating the next time interval, only the earliest one is needed. Compared with the other methods to predict the next time interval, this one does not require large amount of calculations and excessive register resources.

### 3.2. Design of confidence interval for next edge instant

However, Hall signals can not be judged only by using the predicted time instant of the next edge since the real signals are disturbed by various errors and disturbances. Therefore, a confidence interval should be set to exclude the effects of possible errors and disturbances according to certain standard. If the next edge of real Hall signals falls into the confidence interval, Hall signals can be judged to be normal. Otherwise, Hall signals can be judged to be abnormal and needs to be corrected.

Since the time instant of the next edge can be affected by the speed ripple of the motor, installing errors of Hall sensors, mounting errors of rotor magnetic poles, and delay of signal processing circuits, the confidence interval should be designed taking these factors into account. Assume the ripple ratio of the pulse is denoted by $\alpha < 1$, then the minimal width can be set as:

$$\Delta t_{\text{min}} = (1 - \alpha)\hat{\Delta t}$$  \hspace{1cm} (5)

The maximal width can be set as:

$$\Delta t_{\text{max}} = (1 + \alpha)\hat{\Delta t}$$  \hspace{1cm} (6)

Then, the confidence interval of the time instant for the next pulse edge can be derived as:

$$\hat{t}_{k+1} \in [t_k + \Delta t_{\text{min}}, t_k + \Delta t_{\text{max}}]$$  \hspace{1cm} (7)

![Figure 3. Relationship of 3-phase Hall signals in an electrical period.](image-url)
3.3. Design of detection and correction algorithm

If the time instant \( t_k \) of the next real pulse edge falls into the confidence interval (7), Hall signals can be judged to be normal. If \( t_k \) is earlier than \( (t_k + \Delta t_{\text{min}}) \), Hall signals can be judged to be advanced or a pulse is added. If \( t_k \) is later than \( (t_k + \Delta t_{\text{max}}) \), Hall signals can be judged to be retarded or a pulse is missed. The detection and correction algorithm of Hall signals is shown in Figure 4.

![Detection and correction algorithm of Hall signals](image)

**Figure 4.** Detection and correction algorithm of Hall signals.

4. Experimental results

To verify the effectiveness of the proposed approach in this paper, experiments have been carried out by using a BLDCM with pole pairs of 6, rated voltage of 50V, and rated current of 3A. In the experiment, BLDCM is controlled by a FPGA control unit plus 3-phase half bridge and runs at a speed of 3000r/min. To simulate the faults of Hall signals, three switches are used in the signal transmission channels. Opening the switch can cut off the signal transmission to simulate the break faults of Hall signals. The detection and correction algorithm is implemented in FPGA and experimental results are derived when switching off Hall signal of phase B, as shown in Figure 5 and Figure 6. Since Hall signals are reversed by the open collector circuits, high level denotes break fault in the figures.

Switching off \( H_b \) without fault detection and correction, experimental results are shown in Figure 5. From Figure 5(a), it can be seen that \( H_b \) turns into high level due to the break fault and the commutation of phase A becomes abnormal. After the break fault happens, the current \( i_a \) of phase A has large peaks which is harmful to the health of the motor. The current \( I \) of DC link also exceeds the normal value. As a result, the speed in Figure 5(b) drops suddenly.

When Hall signals are detected and corrected by the proposed approach, experimental results are shown in Figure 6. From Figure 6(a), it is known that the faulty Hall signal \( H_b \) is corrected to be \( H'_b \) and the effect of the signal fault on BLDCM is attenuated. Both the current \( i_a \) of phase A and the current \( I \) of DC link have no obvious variations. As a result, the speed in Figure 6(b) also has enough stability. From these results, it can be concluded that the proposed approach is effective.
5. Conclusion
A simple approach is proposed to detect and correct signal faults of Hall position sensors for BLDCMs running at steady speed. This approach only adopts prior information of pulse intervals in the last electrical period and is easy to implement. Experimental results indicate that this approach is feasible.

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