Easy Hall position sensor fault-tolerant control algorithm for brushless DC drives

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Abstract: This paper focuses on Hall-effect sensor fault detection and compensation for brushless dc (BLDC) drives. A methodology based on the Hall position vector phase differences is investigated to detect Hall fault. In order to obtain high-resolution position estimation in fault operation, an improved interpolation position estimation algorithm is described. The method’s most innovative feature is the rapid fault diagnosis. After that, Hall signal noise is analyzed between sampling periods, and a correction machine to filter Hall noise and compensate the filter delay is proposed. Experimental results are shown to validate the effectiveness of the proposed method in the BLDC drive system.

Keywords: BLDC, interpolation algorithm, fault-tolerant control, Hall single noise

Classification: Circuits and modules for electronic instrumentation

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Introduction

Brushless dc (BLDC) motors are becoming very popular in various applications due to their reliable operation, high power density and long life [1]. BLDC motors usually fed by square-wave current require three binary Hall-effect sensors which are displaced at 120° electrical to sense the position of the permanent magnet flux density wave [2, 3]. However, due to the aggressive environment, vibrations or circuit connection faults, Hall-effect sensors are prone to faulty and Hall signals will remain in a high or low state [4]. Thus, fault detection and compensation technology is very critical to ensure the reliability of the BLDC drives.

Most recently, some methods have been proposed to online diagnose Hall sensor fault [5, 6, 7]. In [5], the Fourier transform analysis is performed on the line voltage of the motor. The defective sensor can be detected based on the spectrum energy density of the line voltage frequency spectrum. However, the Fourier transform analysis is computationally expensive and the low fault detection
efficiency. In [6], Hall signals are processed to form a position vector. Any of Hall fault types will lead to the zero position vector. Fault diagnosis based on the zero position vector and next vector adjacent to it is implemented. But the process of fault detection may take a long time, which will induce large torque ripples. In [7], Hall signals are captured at every Hall transition. The information obtained by comparing the captured signals is used for fault diagnosis. This method is robust and improves fault diagnosis efficiency.

In the study of fault-tolerant control, some scholars have proposed the Hall fault compensation methods based on reduced-order observer [8, 9]. However, these methods use the duration between the two successive Hall transitions to estimate the average rotor velocity, which will produce the calculation delay at low speed and cause an estimation error due to the misaligned Hall-effect sensors. In [10], the fault-tolerant control is implemented using a sensorless control algorithm. It increases the design difficulty of the control system and the algorithm depends on mechanical parameters such as inductance and rotor flux. Since the Luenberger-style observer can obviously improve the performance of the control system, vector-tracking observers are an adaptation of the observer has been used extensively in the area of the position sensorless [11, 12]. In addition, in [13] a vector-tracking observer with modified harmonic decoupling is presented to achieve fault-tolerant control, which estimates the rotor position by crossing the decoupled position vector. However, this method requires estimating a high accuracy load torque and a complex harmonic decoupling process. In [14], a methodology based on the Hall zero position vector for fault detection and the orthogonal phase-locked loop with an adaptive notch filter for fault-tolerant control is presented. The adaptive notch filter can remove higher harmonic components from the output of the orthogonal phase-locked loop. And the accurate rotor position and velocity is estimated by its fundamental component. However, in order to obtain the fundamental component in Hall fault operation, the adaptive notch filter need be further modified based on the Fourier transform analysis results of the Hall vectors, which increases the design complexity of the algorithm and decreases fault diagnosis efficiency.

This paper proposes an improved fault-tolerant control technology for BLDC drives. The present manuscript makes the following overall contributions:

1) The paper proposes a simple but very effective fault detection method based on Hall position vector phase differences. The effectiveness of the method is investigated under single and double fault operation.
2) An improved interpolation position estimation algorithm is proposed to implement fault compensation. And a Hall noise immunity and compensation method is used, which can eliminate the signal noise induced by the high-frequency switching characteristics of the inverter [15].
3) The solution can be implemented with BLDC drive system. The steady state and dynamic performances of the drive system are shown with fault situations.

2 Hall sensor fault detection

In BLDC motors, three binary Hall-effect sensors generate discrete position information with a resolution of 60°. Hall signals from the sensors outputs can
be interpreted as a Hall position vector $\mathbf{H}_{a\beta}$. First, a simple operation converts Hall signals ($H_1, H_2, H_3$) into three Hall states ($H_a, H_b, H_c$) by (1), which are equal to 1 or $-1$ when the related Hall signals ($H_1, H_2, H_3$) is at high or low level.

$$
\begin{pmatrix}
H_a \\
H_b \\
H_c
\end{pmatrix} = 2
\begin{pmatrix}
H_1 \\
H_2 \\
H_3
\end{pmatrix} - 1
$$

(1)

Next, according to the Clark transform the vector $\mathbf{H}_{a\beta}$ can be expressed as

$$
\begin{pmatrix}
H_a \\
H_\beta
\end{pmatrix} = \frac{\pi}{4}
\begin{pmatrix}
1 & -\frac{1}{2} & -\frac{1}{2} \\
\frac{\sqrt{3}}{2} & 0 & -\frac{\sqrt{3}}{2}
\end{pmatrix}
\begin{pmatrix}
H_a \\
H_b \\
H_c
\end{pmatrix}
$$

(2)

where $H_a$ and $H_\beta$ are the coordinate components of $\mathbf{H}_{a\beta}$ in the $a\beta$ stationary reference frame. Fig. 1(a) depicts the locus and phase differences of $\mathbf{H}_{a\beta}$ under normal operation, wherein the phase differences ($\theta_{11}, \theta_{12}, \theta_{13}$) are calculated at Hall transitions. Note that the absolute values of $\theta_{11}$, $\theta_{12}$ and $\theta_{13}$ are equal to 180°.

Here, an online fault detection method is proposed that uses the phase differences ($\theta_{11}, \theta_{12}, \theta_{13}$), which can improve the fault diagnosis effectiveness. If any sensor is damaged, the related Hall transition will not be captured, resulting in the change of phase differences. In Fig. 1(b), it is assumed that the single fault ($H_1 = 1$) occurs, the phase differences $\theta_{12}$ and $\theta_{13}$ are equal to $-240°$ and $360°$ respectively. The phases of $\mathbf{H}_{a\beta}$ corresponding to the Hall signals (111) and (000) are defined as 360°. Meanwhile, in the other 5 single fault types, the phase differences corresponding to the remaining sensors possess their specific value. The possible phase differences are summarized in Table I. Thereafter, the signal fault type can be detected at Hall transitions using the lookup table (see Table I).

If the double fault ($H_1 = 1, H_2 = 1$) occurs, the locus and phase differences of $\mathbf{H}_{a\beta}$ are shown in Fig. 1(c). As can be seen, $\theta_{11}$ computed at the rising or falling...
edges of $H_3$ is equal to $300^\circ$. However, the above fault detection method will not applicable since the phase differences $\theta_{1x}$ may be the same in 18 possible fault types, which cause misdiagnosis in the process of fault detection. Therefore, a method that combines the related defective Hall signal and phase differences in the process of some double fault types can potentially address the problem. Finally, the double fault type can be determined according to Table II.

Table I. Signal Hall sensor fault type detection method

| Fault type $/C_{18}$ | $\theta_{11}$ | $\theta_{12}$ | $\theta_{13}$ |
|----------------------|--------------|--------------|--------------|
| $H_1 = 1$            | $-240^\circ$ | $360^\circ$  |              |
| $H_1 = 0$            | $-120^\circ$ | $-180^\circ$ |              |
| $H_2 = 1$            | $240^\circ$  |              | $120^\circ$  |
| $H_2 = 0$            | $-60^\circ$  |              |              |
| $H_3 = 1$            | $120^\circ$  |              |              |
| $H_3 = 0$            | $-120^\circ$ | $-300^\circ$ |              |

Table II. Double Hall sensor fault type detection method

| Fault type $/C_{18}$ | $\theta_{13}$ |
|----------------------|--------------|
| $H_1 = 1$, $H_2 = 1$ | $\theta_{13} = 300^\circ$ |
| $H_1 = 1$, $H_2 = 0$ | $\theta_{13} = -60^\circ$ |
| $H_1 = 0$, $H_2 = 1$ | $\theta_{13} = 60^\circ$ |
| $H_1 = 0$, $H_2 = 0$ | $\theta_{13} = -120^\circ$ |
| $H_1 = 1$, $H_3 = 1$ | $\theta_{12} = 60^\circ$, $H_3 = 1$ |
| $H_1 = 1$, $H_3 = 0$ | $\theta_{12} = 60^\circ$, $H_3 = 0$ |
| $H_1 = 0$, $H_3 = 1$ | $\theta_{12} = -60^\circ$ |
| $H_1 = 0$, $H_3 = 0$ | $\theta_{12} = -240^\circ$, $H_1 = 0$ |
| $H_2 = 1$, $H_3 = 1$ | $\theta_{11} = -180^\circ$ |
| $H_2 = 1$, $H_3 = 0$ | $\theta_{11} = -60^\circ$, $H_2 = 1$ |
| $H_2 = 0$, $H_3 = 1$ | $\theta_{11} = 60^\circ$ |
| $H_2 = 0$, $H_3 = 0$ | $\theta_{11} = -360^\circ$ |

3 Fault-tolerant control

Hall sensor fault can be quickly diagnosed based on the fault detection strategy proposed in Section 2. To construct a better estimation position, fault-tolerant control adopts an improved interpolation position estimation algorithm, including three parts: speed and acceleration estimation, position estimation and Hall signal noise immunity and compensation as shown in Fig. 2.

A. Estimation of speed and acceleration

In Fig. 3(a), $t_{i-2}$, $t_{i-1}$, $t_i$ and $t_{i+1}$ are treated as the transient moments of Hall sensors, and $T_{Hall}(t_i)$ as the duration between the two consecutive Hall transitions at moments $t_{i-1}$ and $t_i$. According to the first-order interpolation estimation algorithm, the speed $\omega(t_i)$ at $t_i$ is calculated as

$$\omega(t_i) = \omega(t_{i-1}) + a(t_{i-1}) \cdot T_{Hall}(t_i)$$

where $a$ is the motor acceleration that keeps constant during $60^\circ$ electrical degree.
According to (3), the average speed in the time interval \([t_{i-1}, t_i]\) is given by (4) as

\[
\tilde{\omega}(t_i) = \frac{\pi}{3} \frac{\omega(t_{i-1}) + \omega(t_i)}{T_{Hall}(t_i)} = \frac{\omega(t_{i-1}) + \omega(t_i)}{2} \cdot \frac{T_{Hall}(t_i)}{2}
\]

(4)

Thus, from (3) and (4), the estimated speed at \(t_i\) can be expressed as

\[
\tilde{\omega}(t_i) = \tilde{\omega}(t_{i-1}) + \tilde{a}(t_{i-1}) \cdot \frac{T_{Hall}(t_i)}{2}
\]

(5)

and the average acceleration at \(t_i\) can be expressed as

\[
\tilde{a}(t_i) = \frac{\tilde{\omega}(t_i) - \tilde{\omega}(t_{i-1})}{T_{Hall}(t_i)}
\]

(6)

Assuming \(t_{i,k}\) is between \(t_i\) and \(t_{i+1}\), the estimated speed at \(t_{i,k}\) is calculated as

\[
\tilde{\omega}(t_{i,k}) = \tilde{\omega}(t_i) + \tilde{a}(t_i) \cdot (t_{i,k} - t_i)
\]

(7)

Fig. 2. Block diagram of fault-tolerant control system

However, the problem on BLDC motors with unbalanced Hall sensors still exists. The speed estimation error may be quite significant due to unbalanced operation of the inverter [16]. In order to address this problem, the duration \(T_{mi}\) between the moments at the rising and falling edges of a Hall signal is used to compute the average speed as shown in Fig. 3(b). Nevertheless, since the speed is updated every a complete electrical period, the speed delay will be serious at low speed. In order to minimize the effect of the average speed, a solution will be applied: at Hall commutations a correct speed is computed using the duration \(T_{mi}\) and at each 60° electrical degree, which can reduce the speed delay and estimation error caused by misalignment Hall sensors. Considering that a large acceleration may make the speed suffer from estimation delay, as well as decrease overall control system performance. To further better improve the speed estimation

Fig. 3. (a) Speed estimation from Hall commutation. (b) Duration during one electrical period
resolution, a speed correction using the ratio between the Hall signal commutation moments of two consecutive transitions of same Hall state is adopted. The speed response can be quickly detected. The average speed can be given by (8) as

\[
\tilde{\omega}(t_{m,i}) = \tilde{\omega}(t_{m-1,i}) \cdot \frac{t_{m-1,i-1}}{t_{m-1,i}} = \frac{2\pi}{T_{(m-1)}} \cdot \frac{t_{m-1,i-1}}{t_{m-1,i}}
\]

In (8), the moment \(t_{m,i}\) is reset to zero every six Hall transitions. Relation (8) instead of (4) is applied to (5) and (7) for the computation of the estimation speed.

B. Estimation of the rotor position

Once the speed and acceleration are estimated using relation (7), the estimation position can be found as follows

\[
\hat{\theta}(t_{i,k}) = \theta_0(t_i) + \tilde{\omega}(t_i) \cdot (t_{i,k} - t_i) + \frac{1}{2} \tilde{\omega}(t_i) \cdot (t_{i,k} - t_i)^2
\]

where \(\theta_0(t_i)\) is the actual rotor position at Hall transitions. An approach of aligning the estimation position at every Hall transition until it is equal to the actual position \(\theta_0\) has been proposed, which is not very practical especially for BLDC motors since the problem on unbalanced Hall sensors introduces additional position estimation error. To obtain the high-resolution position estimation, a gradual correction is used. At the every Hall commutation, the position error \(\Delta \theta_0(t_i)\) should be

\[
\Delta \theta_0(t_i) = \theta_0(t_i) - \hat{\theta}(t_i)
\]

As shown in (11), the position error \(\Delta \theta_0(t_i)\) will be evenly distributed in the next Hall sector, which can achieve self-correction of rotor position.

\[
\hat{\theta}(t_{i,k}) = \hat{\theta}(t_{i,k}) + \Delta \theta_0(t_i) \cdot \frac{(t_{i,k} - t_i)}{(t_i - t_{i-1})}
\]

C. Hall noise immunity and compensation

In particular, the high-frequency switching characteristics of the inverter may induce Hall signal noise in BLDC drive system. Even if such signal noise persists for a short time, the Hall misdiagnosis situation may appear. Herein, a finite state machine is adopted for filtering Hall signal noise. It is composed of the Hall transitions and a counter. If the rising edge of Hall signal is captured, the counter will be incremented. The inverter will commutate when the counter reaches \(N\). Likewise, the commutation point of the inverter will advent as the falling edge of Hall signal is captured and the counter is decremented to zero. The value of \(N\) is defined as

\[
N = \frac{t_g}{t_{sample}}
\]

\(t_{sample}\) and \(t_g\) are the sampling time and the commutation delay respectively. In this way, the inverter commutation is delayed. An increase in torque ripple and acoustic noise during high speed operation will be produced. However, the proposed fault-tolerant technology control can be further optimized to compensate for the delay. The estimated position error caused by the delay can be calculated as

\[
\theta_{delay} = \tilde{\omega}(t_i) \cdot t_g
\]

The position error \(\Delta \theta_0(t_i)\) can be recalculated by (14). Based on (11) and the new \(\Delta \theta_0(t_i)\), the optimized estimation position can be given as follows

\[
\theta(t_{i,k}) = \theta_0(t_i) + \Delta \theta_0(t_i) \cdot \frac{(t_{i,k} - t_i)}{(t_i - t_{i-1})} = \theta_0(t_i) + (\theta_0(t_i) + \theta_{delay} - \theta_0(t_i)) \cdot \frac{(t_{i,k} - t_i)}{(t_i - t_{i-1})}
\]
4 Implementation and verification

Fig. 4 shows the block diagram of the BLDC experimental drive system. A TM320F2812 type digital signal processor is used to allow flexibility in the proposed control method implementation and drive the machine through a full bridge IGBT inverter with switching frequency of 20 kHz. The inverter utilizes a 36 V power source as its input. The fault-tolerant control system is used to detect, compensate Hall fault and estimate the speed and position of rotation. The main parameters of the BLDC motor are summarized in Table III.

| Table III. Main parameters of the BLDC motor |
|------------------------------------------------|
| Rated voltage | 36 [V] |
| Pole pairs | 2 |
| Rated current | 13 [A] |
| Rated speed | 3000 [r/min] |
| Rated power | 350 [W] |
| No-load current | 0.5 [A] |
| Rated torque | 1.2 [N·m] |

In order to demonstrate the effectiveness of the fault detection and compensation method described above, several tests have been performed. The steady state performance of the drive system is analyzed during single and double faults by some suitable experimental tests. In order to highlight the dynamic behavior, the studies with single and double faults have been considered under conditions of acceleration and variable load.

4.1 Single and double fault operation

In the first study the tests, shown in Fig. 5 and 6, those in single or double fault operation based on different fault locations are performed to verify the steady state performance of the proposed method. Fig. 5 shows the experimental results in single fault operation for the speed reference 300 r/min and no load. Hall signals H₁ and H₂, the phase current Iₘ and the estimation position θ are all shown. As can be seen in Fig. 5(a), the single fault (H₁ = 1) occurs when H₁ is at high level. After approximately 45 ms, the fault is diagnosed and compensated at the rising edge of H₃.

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However, there does not exist the position oscillation and abnormal phase current in the process of fault-tolerant control, and the position error $\Delta \theta(t_f)$ is close to zero since $H_1$ is high level before the $H_1 = 1$ fault. Fig. 5(b) shows that when $H_1$ is at low level, the single fault $H_1 = 1$ is emulated. And the rising edge of $H_1$ is generated leading to $\theta(t_f) = 270^\circ$, which produces a large position estimation error close to $60^\circ$. This in turn causes the reverse phase current. But it lasts about 15 ms until the falling edge of $H_2$ is captured. Therefore, in single fault operation no matter where fault occurs, fault detection and compensation can be fleetly carried out within $240^\circ$ electrical.

Fig. 5. Fault detection and compensation under single fault operation

Correspondingly, Fig. 6 shows the experimental results with double fault ($H_1 = 1, H_2 = 1$) in the same operation conditions. Similar to single fault, $\Delta \theta(t_f)$ may be disordered depending on where double fault occurred. Since the rising and falling edges of Hall signals reduce, the duration of fault detection may increase, for instance which is about 37 ms and 52 ms correspondingly to Fig. 6(a) and (b) respectively. Also, at Fig. 6(b), a dip in the estimation position is $20^\circ$ and the current ripple is approximately $80\%$ of the normal current in the process of the fault diagnosis. However, the machine can recover normal operation less than half of an electrical period. This result is consistent with previous observations regarding the single fault (see Fig. 5), wherein the proposed fault-tolerant control method performed well under faulty condition.

Fig. 6. Fault detection and compensation under double fault operation

4.2 Transient performance

Other studies are performed to evaluate the dynamic performance of the proposed method in faulty conditions. The corresponding results are shown in Fig. 7. An
acceleration transient is implemented by stepping the reference speed from 260 r/min to 800 r/min with no load during single and double fault operation. The corresponding transient responses recorded with the proposed method are shown in Fig. 7a) and b). As can be seen, the acceleration transient is completed within 85 ms and the speed of rotation reaches to 800 r/min. Under single fault ($H_1 = 1$) operation, the estimation position is unbalanced and spiky when the speed transient occurs and the maximum position estimation error is $15^\circ$ electrical. The current dips by approximately 100% of the phase current. However, the position can be accurately estimated and the motor recovers normal operation after 0.1 s. Similarly, the maximum position estimation error is $23^\circ$ electrical during double fault ($H_1 = 1, H_2 = 1$) operation and the current reaches 1.1 A, dipping by 120% of the phase current. The duration of the whole transient lasts 110 ms. In other single or double faulty conditions, the speed transient lasts about 0.1 s, and the smaller position estimation error and current oscillation are produced similar to Fig. 7a) and b). Therefore, it can be verified that the proposed fault-tolerant control method has good dynamic performance under acceleration process.

To enable faster mechanical transients, the experiments of variable load (20%~80% of rated torque) with 500 r/min are performed during single fault ($H_1 = 1$) and double fault ($H_1 = 1, H_2 = 1$) operation. Fig. 7c) and d) shows the corresponding results. Initially, the machine was assumed to run in the single or double fault conditions at 500 r/min and at a 0.24 N·m load. After 2 s, the load torque was stepped and gradually increases to 80% of rated torque. As expected, the current gradually increase until it remains stable and has a smaller dip. The drive system still maintains stable operation in the process of the load step. It has not obvious vibration, and the maximal position estimation error is less than $8^\circ$ electrical.

![Fig. 7. Speed transient or load increasing during single or double fault operation](image-url)
in \( H_1 = 1 \) fault. While in \( H_1 = 1, H_2 = 1 \) fault the small vibration exists in the current and the maximal estimation error reaches to 15°, but a faster recovery time.

Finally, Fig. 8 shows the phase current waveforms before and after Hall noise compensation. In order to verify the effectiveness of the Hall noise compensation method, the reference speed of rotation is set to 1800 r/min. Considering that the duration of Hall signal noise is millisecond, \( N \) and the sampling frequency are set to 10 and 40 kHz respectively. As shown in Fig. 8, before noise compensation the commutation delay is set to 0.25 ms to filter the Hall signal noise, which leads to sufficient current ripple reaching to 150% of the normal current. This in return increases the torque ripple and deteriorates the motor performance. However, the maximal current ripple is reduced to 70% of the normal current after the compensation method used, and the motor performance will be visibly improved.

5 Conclusions

This paper proposed an easy Hall sensors fault detection and compensation method. Hall sensor faults (single fault and double fault) have been analyzed, and the Hall vector phase differences at Hall transitions will be different in faulty conditions, in addition each fault type is associated to a specific phase differences. The fastest possibly identification of fault type is achieved by recognizing the differences. An improved interpolation position estimation algorithm has been applied to implementing fault-tolerant control, which ensures the high-resolution position estimation in fault operation and eliminates Hall single noise. The steady state and dynamic performances of the proposed method is verified experimentally on BLDC drive. The fault-tolerant control system can quickly detect and compensate Hall fault and has good performance in steady state and transient (such as, large acceleration and variable load) under fault operation of up to two Hall sensors. Furthermore, the effect of the Hall noise is obviously improved in high speed.

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