Fault Diagnosis and Fault-tolerant Control of Position Sensors for Switched Reluctance Motors

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Abstract: Position sensor is the key of exact commutation for switched reluctance motor (SRM). When position sensor is faulted, some phase information of commutation will be lost, causes torque decrease, affects the system reliability. Through the analysis of the fault position signals, a real-time diagnostic method that detected the edge sequences of position signals and calculated the angle between the adjacent edges of position signals is proposed. After fault of position signal is diagnosed, fault-tolerant control is carried out immediately by taking advantage of the redundant information of position signal detection scheme and the time between the adjacent edges of position signals. The validity and practicability of fault analysis, fault diagnosis and fault-tolerant control is verified by simulated fault experiments on SRM. Copyright © 2013 IFSA.

Keywords: Switched reluctance motor (SRM), Position signal, Fault analysis, Fault diagnosis, Fault-tolerant control.

1. Introduction

Switched reluctance motor (SRM) has the advantages such as simple and solid structure, low cost, flexible control, strong fault-tolerant ability, and good adaptability to high temperature and high speed, etc., so it is especially suitable for some application fields in which the environment is abominable and the system is required to work continuously, such as aviation start/power generation system, vehicle-loaded electric braking system, and mine hoist, etc. [1-7].

SRD (switched reluctance driver) system works in synchronous state. Position closed-loop is a basic condition for the normal work of the system, and also one of the important marks which distinguish SRD from stepper motor. By processing the correct position signals produced by position sensors, SRD system controls the break-over sequence and time of the winding of each phase, and ensures the commutation at correct position and the operation toward predetermined objective of motor. Position sensor is generally installed together with the motor itself, and is easy to go out of order for the functions of severe environment like dust, oil stain, and collision, etc., the fault of position signal will induce open-phase running of motor, lower the output torque of motor, and affect the reliability of system operation. Therefore, for meeting the requirement of high reliability, it’s very necessary to carry out real-time fault diagnosis and fault-tolerant control aiming at the feedback signal of position sensor.

Predecessors have carried out plentiful researches on the fault diagnosis and fault-tolerant control of
brushless motor systems like switched reluctance motor, brushless DC motor and doubly salient motor, etc. [8-16], and documents [11-16] have mentioned the fault of position signal and analyzed the influences of fault on the system. Wherein, document [13] has realized the fault-tolerant control of 8/6 switched reluctance motor by adding two position sensors, but not analyzed the scheme for fault diagnosis and fault-tolerant control of position sensors in detail; document [14] has analyzed the fault type and mechanism of Hoare signal, and state after fault of dually salient permanent magnet motor in detail, but not presented the scheme for sequent processing; document [15] has researched the position signal of doubly salient motor, and on this basis, brought forward the method for fault diagnosis, reconstructed the commutation logic of position sensor signal, and realized fault-tolerant control after fault, but in case the rotation rate changes greatly, the fault diagnosis of position signal will have a low reliability. Document [16] has analyzed the influence of position sensor fault on switched reluctance motor, brought forward the method of introducing diagnosis buffer area to realize fault detection, and reconstructed the commutation action after fault, but in case the diagnosis buffer time is over long, the open-phase running during diagnosis buffer period will produce heavy impact on the work of system.

By researching the position signal of SRD system, this paper has brought forward a method for monitoring the running state of position signal in a real-time way. This method enables the timely diagnosis on the type of position signal fault, and can realize the fault-tolerant control of position signal during operation. The experimental result has proved the validity of the scheme.

2. Analysis on Faulted Position Signal of Sensors

2.1. Overview on the Position Signal of Switched Reluctance Motor

Photosensitive position sensor has simple circuit and relatively high detection precision, and so has been widely applied to SRD system as well as brushless DC motor and doubly salient motor. It generally consists of photoelectric pulse generator and turntable.

This paper takes one three-phase 12/8 prototype as research object, as shown in Fig. 1. Here, rotor polar angle \( \tau_r = 45^\circ \), and three photoelectric pulse generators P, Q, R are fixed onto the stator, the position difference is 60° in turn. The gear-groove ratio of the detecting turntable for the position detection system is 2:1, and the angle resolution available to get by relying on the electric level combination of position signal is 15°. And in case of edge jump of position signals, among the three detected signals, there will always be one falling edge and one raising edge appearing simultaneously. So, the position detection scheme can realize the direct output of redundant information, and is beneficial for real-time fault-tolerant control.

![Fig. 1. Installation of position sensors for SRM.](image)

In SRD system, DSP produces the control signals necessary for the ON and OFF of each phase according to the position signals output by position sensors P, Q and R. Here, the angle signal classification is not considered, and it’s assumed that \( P \uparrow \Rightarrow A \) phase ON, \( Q \uparrow \Rightarrow B \) phase ON, \( R \uparrow \Rightarrow C \) phase ON, \( P \downarrow \Rightarrow A \) phase OFF, \( Q \uparrow \Rightarrow B \) phase OFF, \( R \uparrow \Rightarrow C \) phase OFF, where “\( \uparrow \)” indicates falling edge, and “\( \downarrow \)” indicates rising edge.

2.2. Analysis on Faulted Position Signal of One Phase

The fault of one-phase position signal may be the fault of any phase among the three phases of position signals corresponding to sensors P, Q and R. The three phases are symmetrical, so the fault of P-phase position signal is taken as an example for analysis. In Fig. 2, P signal arrow shows the fault position, broken line indicates the signal state after fault, while the broken line in \( K_a \) indicates the break-over ON/OFF state of phase A after fault.

As shown in Fig. 2(a), low level fault occurs to P signal. After occurrence of fault, phase A will always maintain the ON state, while other Q and R signals will be normal, and corresponding phases B and C will execute commutation normally. So, after sensor P has low level fault, phases B and C will have normal output, while phase A will be always ON. The follow current of Phase A cannot be zero. Here, braking torque is output in the interval \( dL_3 / d\theta < 0 \), and the electromagnetic output torque arousing the positive-negative alternation of phase A severely destroys the balanced state of system and induces the violent fluctuation of motor’s rotation rate.
As shown in Fig. 2(b), high level fault occurs to P signal. After occurrence of fault, Phase A will always maintain the OFF state, phases B and C will similarly work normally without being affected by the fault of sensor P, and here, motor will be in open-phase running. It’s available to compensate the torque loss of faulted phase by enlarging the excitation of other normal phases, but the total output capacity of the system will be reduced by 1/3.

In case of P high Q low, phase A will always be maintained the OFF state, phase B will always be maintained the ON state, and motor will be in open-phase running. The overall output performance of the system will be deteriorated, and even, the motor will possibly not work normally. The analysis on P low Q high is the same as above.

In case of P low Q high, phases A and B will always be maintained the OFF state, while phase C will be ON and OFF at correct position. Therefore, phase B will have the positive-negative alternating fluctuation of electromagnetic output torque, and this will destroy the balanced state of system and induce the violent fluctuation of motor’s rotation rate; while phase A will be always OFF, and motor will be in open-phase running. The overall output performance of the system will be deteriorated, and even, the motor will possibly not work normally. The analysis on P low Q high is the same as above.

In case of P high and Q high, phases A and B will always be maintained the OFF state, phase C will be ON and OFF at correct position, the motor will be in open-phase running, and the total output capacity of the system will be 1/3 of the original one.

2.3. Analysis on Faulted Position Signal of Two Phases

The faulted position signals of sensors P and Q are taken as examples for analysis. The faulted position signals of the two sensors may be divided into four types, namely P high and Q high, P low and Q low, P high and Q low, and P low and Q high.

In case of P low Q low, P and Q always maintain a low level after low level fault of position signal, and among the three position signals, only R signal still has edge jump. Therefore, corresponding phases A and B are always maintained the ON state, while phase C is ON and OFF at correct position. The low level fault is the same for single sensor, and the phase winding corresponding to P and Q fault signals outputs positive-negative alternating electromagnetic torque. This severely deteriorates the output performance of the system, and makes it impossible for the motor to work.

In case of P high Q low, phase A will always be maintained the OFF state, phase B will always be maintained the ON state, while phase C will be ON and OFF at correct position. Therefore, phase B will have the positive-negative alternating fluctuation of electromagnetic output torque, and this will destroy the balanced state of system and induce the violent fluctuation of motor’s rotation rate; while phase A will be always OFF, and motor will be in open-phase running. The overall output performance of the system will be deteriorated, and even, the motor will possibly not work normally. The analysis on P low Q high is the same as above.

In case of P high and Q high, phases A and B will always be maintained the OFF state, phase C will be ON and OFF at correct position, the motor will be in open-phase running, and the total output capacity of the system will be 1/3 of the original one.

2.4. Analysis on Faulted Position Signal of Three Phases

In case of faulted position signal of sensors P, Q and R, the position signal output will be constantly high or low, DSP will have no edge information to capture, and each phase will be maintained at the final ON or OFF state. Meanwhile, DSP usually calculates real-time rotation rate through position signal, so under such fault, controller cannot update the rotation rate information. Therefore, when all the three sensors become invalid, motor will operate by dint of inertia under constant control signal, and the braking torque and load torque constantly produced by the break-over phase will make the motor stop running finally.

3. Analysis on Faulted Position Signal of Sensors

During the normal operation of motor, in case the rotation direction is unchanged, the sequence for the three position sensors to produce jump edge will be fixed, so will the angle difference between adjacent jump edges. Therefore, when a position sensor has fault, the producing sequence of jump edge or the angle difference between adjacent jump edges will change, and DSP will judge the fault of position signals by detecting the characteristics of such faults.

This paper connects the position signals of sensors P, Q and R to the capture ports CAP4, CAP5 and CAP6 of DSP respectively, triggers interruption at the falling edge of each position signal, enters into edge capture interruption subprogram, transfers position signal diagnosis program, and outputs commutation logic. It’s known from Fig. 3 that, the
correct falling edge triggering sequence is \( R \downarrow - Q \downarrow - P \downarrow - R \downarrow - Q \downarrow - P \downarrow - \ldots \), which appears periodically and repeatedly.

![Image](image_url)  
**Fig. 3.** Falling edge sequence of position signals.

### 3.1. Fault Diagnosis when the Position Signal is Consistent before and after Fault

High level fault diagnosis will be analyzed firstly. Position signal is high level constantly before and after fault, so after occurrence of fault, falling edge triggering signal won’t be formed, and we can diagnose the fault type according to the phase sequence of falling edge. Here, P signal fault is taken as example for analysis. As shown in Fig. 4, Fig. 4(a) indicates the high level fault in interval I, and Fig. 4(b) indicates the high level fault in interval II. After high level fault of P signal, the triggering sequence of falling edge will become \( Q \downarrow - R \downarrow \), without \( P \downarrow \) after \( Q \downarrow \), so we can judge that sensor P has fault. Similarly, in case the triggering sequence of falling edge is \( R \downarrow - P \downarrow \), without \( Q \downarrow \) after \( R \downarrow \), then we can judge that sensor Q has fault; and in case the triggering sequence of falling edge is \( P \downarrow - Q \downarrow \), without \( R \downarrow \) after \( P \downarrow \), then we can judge that sensor R has fault.

![Image](image_url)  
(a) High level fault I; (b) High level fault II.

In case both P and Q position signals have high level faults simultaneously, they won’t be able to form falling edge and trigger interruption. Here, only R signal can produce falling edge and trigger interruption, and the triggering sequence of falling edge is \( R \downarrow - R \downarrow - \ldots \), without \( P \downarrow \) and \( Q \downarrow \), so we can judge that, sensors P and Q have faults. Similarly, in case only P signal can produce falling edge and trigger interruption, then sensors Q and R have faults; and in case only Q signal produces falling edge and trigger interruption, then sensors P and R have faults.

For the fault diagnosis of position signal on high level maintained, please refer to Table 1.

<table>
<thead>
<tr>
<th>Previous falling edge signals</th>
<th>Present falling edge signals</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R \downarrow )</td>
<td>P and Q phases fault</td>
</tr>
<tr>
<td>( Q \downarrow )</td>
<td>P phase fault</td>
</tr>
<tr>
<td>( P \downarrow )</td>
<td>No fault</td>
</tr>
</tbody>
</table>

The following will analyze the fault diagnosis of position signal on low level maintained. Similarly, P signal fault is taken as example to analyze the method for diagnosing single-phase low level fault. As shown in Fig. 5, the signal state is accordant before and after fault, so no falling edge will be produced to trigger interruption. But here, the triggering sequence of falling edge is \( P \downarrow - R \downarrow - Q \downarrow \), and the signal triggering sequence is correct, so it’s impossible to judge the fault type immediately only according to the signal triggering sequence. It’s found from analysis that, normally, after the falling edge of R signal triggers capture interruption, the three-phase position signal level will be 011b, which will be maintained until the next falling edge; similarly, after Q signal enters capture interruption, the value of three-phase position signal will be 101b; and after P signal enters capture interruption, the value of three-phase position signal will be 110b. Therefore, after falling edge triggers interruption, we may judge whether the system has faults and the fault type through real-time detection of three-phase position signal level. For detailed fault diagnosis, please refer to Table 2. As shown in Fig. 5, low level position signal fault appears in interval III, and at \( R \downarrow \) thereafter, the three-phase position signal read is 010b; according to Table 2, we may know that sensor P has faults. This proves the validity of the method. The method for diagnosis of two-phase low level fault is the same as above.

To sum up, for the fault diagnosis when position signal is accordant before and after fault, every time after low level triggering interruption, we shall firstly...
judge the fault type by referring to Table 1 and according to the sequence of falling edge; if there is no fault, we shall then read the value of three-phase position signals, and judge the fault type by referring to Table 2.

\[ P \]
\[ Q \]
\[ R \]
\[ \phi \]
\[ 0 \]
\[ 15 \]
\[ 30 \]
\[ 45 \]
\[ 60 \]
\[ 75 \]
\[ \theta \]

**Fig. 5.** Fault diagnosis when position signal is low level before and after P sensor’s fault.

**Table 2.** Fault diagnosis of position signal on low level maintained.

<table>
<thead>
<tr>
<th>Three-phase level</th>
<th>Present falling edge signal</th>
<th>Fault type</th>
</tr>
</thead>
<tbody>
<tr>
<td>001</td>
<td>R</td>
<td>Q phase fault</td>
</tr>
<tr>
<td></td>
<td>Q</td>
<td>R phase fault</td>
</tr>
<tr>
<td>010</td>
<td>R</td>
<td>P phase fault</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>R phase fault</td>
</tr>
<tr>
<td>100</td>
<td>Q</td>
<td>P phase fault</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>Q phase fault</td>
</tr>
<tr>
<td>000</td>
<td>R</td>
<td>P and Q fault</td>
</tr>
<tr>
<td></td>
<td>Q</td>
<td>R and P fault</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>R and Q fault</td>
</tr>
</tbody>
</table>

**3.2. Fault Diagnosis when Position Signal is Different before and after Fault**

In case the position signal is different before and after fault, it will result in edge jump of position signal, and the falling edge of signal will trigger DSP capture interruption and possibly result in wrong commutation logic.

In case position signal is normally high level, then it will be low level constantly after fault, a falling edge will be formed in case of fault, and the falling edge will trigger DSP capture interruption. Here, P signal fault is taken as example for analysis, as shown in Fig. 6. In interval I as shown in Fig. 6(a), DSP detects that the falling edge of P signal triggers interruption, and the triggering sequence is \( R_1 \rightarrow P \downarrow \rightarrow Q \downarrow \), which is wrong, but the wrong sequence at the moment is possibly corresponding to multiple fault types, so we cannot diagnose the detailed fault type immediately. In interval II as shown in Fig. 6(b), falling edge triggering signal is produced, and the triggering sequence is \( Q_1 \rightarrow P_1 \downarrow \rightarrow R \downarrow \), which is correct, and the system considers that it’s normal interruption, and so changes the commutation logic, makes the system triggering logic in chaos, and lowers the motor output torque. Therefore, it is inapplicable to Fig. 6(b) by only adopting the diagnosis method for edge jump sequence of position signal in section 3.1.

\[ P \]
\[ Q \]
\[ R \]
\[ \phi \]
\[ 0 \]
\[ 15 \]
\[ 30 \]
\[ 45 \]
\[ 60 \]
\[ 75 \]
\[ \theta \]

**Fig. 6.** Fault diagnosis when position signal is different before and after P sensor’s fault; (a) Falling edge fault I; (b) Falling edge fault II.

In case position signal forms a rising edge after fault, we will still take P signal fault as example for analysis. Position signal forms a rising edge, which won’t trigger DSP capture interruption, and so won’t output commutation logic; hereafter, we may diagnose the fault type according to Table 1 with the fault diagnosis method stated in section 3.1.

Through the abovementioned analysis, we need to improve the method in section 3.1. Besides fault analysis with the edge jump sequence of position signals, we shall still introduce the angle difference between adjacent jump edges. As shown in Fig. 7, the time interval of two adjacent correct falling edge jump signals is \( T \). In case the time from the occurrence of previous correct falling edge jump signal to the occurrence of present falling edge jump signal is less than \( T \), then the present falling edge jump signal is fault signal. In actual operation, for relatively low precision of motor’s rotation rate, the calculated angle difference between two adjacent falling edges of normal signals is allowed to be \( 15^\circ \pm 0.5^\circ \), so here, \( T \) is divided into \( t_1 \) and \( t_2 \) by proportion, and wherein, \( t_1 = \frac{29T}{30} \), \( t_2 = \frac{T}{30} \). Any edge-triggered interruption, as captured in \( t_1 \) is considered incorrect interruption.

For the change of motor’s rotation rate, \( T \) is not fixed, and especially at low-speed start stage and high-speed braking stage, the change rate of \( T \) in two
adjacent intervals may be up to more than 50%. Therefore, the diagnosis method depends on the effective adjustment of T value, or the time quantum determined based on fixed T value is non-reliable for the fault diagnosis of position signal.

4. Fault-tolerant Control of Sensor Position Signal

After determining the fault type of position sensor through diagnosis procedure, we may reconstruct the commutation logic corresponding to faulted position signal aiming at different fault types, and thus enable sustained operation of SRD system when partial position sensors go invalid.

4.1. Fault-tolerant Control of One-phase Position Signal

For one-phase position signal fault, we may know from Fig. 2 that, among three position signals, we can always see the simultaneous appearance of a falling edge and a rising edge, so this position signal detection scheme can enable the direct output of redundant information, and realize fault-tolerant control. With the position signal fault of sensor R as example, as shown in Fig. 8, P\textsuperscript{\uparrow} and R\textsuperscript{\downarrow} appear simultaneously, so do P\textsuperscript{\downarrow} and Q\textsuperscript{\uparrow}, so the position signal of P is set to be double-edge triggering to realize the redundancy control of R\textsuperscript{\downarrow} and Q\textsuperscript{\uparrow}. However, Q\textsuperscript{\downarrow} and R\textsuperscript{\uparrow} do not have redundant position information output, so their position signals need to be reconstructed by dint of P’s edge signal. As shown in Fig. 9, we shall read the time interval T of two edge jumps, as comparative value of timer, from the edge jump interruption program of P\textsuperscript{\downarrow} first and then P\textsuperscript{\uparrow} each time; then in case of P\textsuperscript{\uparrow}, we shall clear out the value of counter and restart the counting; when the counted value is equal to the comparative value, it will enter into the timer interruption program, DSP will output the corresponding commutation logic in case of Q\textsuperscript{\downarrow} and R\textsuperscript{\uparrow}, and thus realize the fault-tolerant control of two-phase position signal of Q and R. However, during the accelerated or decelerated operation of SRM, the time interval T of position signal is varying. So we need to calculate T to obtain higher-precision time interval T.

4.2. Fault-tolerant Control of Two-phase Position Signal

The position signal fault of sensors Q and R is taken as example, as shown in Fig. 8. P\textsuperscript{\uparrow} and R\textsuperscript{\downarrow} appear simultaneously, so do P\textsuperscript{\downarrow} and Q\textsuperscript{\uparrow}, so the position signal of P is set to be double-edge triggering to realize the redundancy control of R\textsuperscript{\downarrow} and Q\textsuperscript{\uparrow}. However, Q\textsuperscript{\downarrow} and R\textsuperscript{\uparrow} do not have redundant position information output, so their position signals need to be reconstructed by dint of P’s edge signal. As shown in Fig. 9, we shall read the time interval T of two edge jumps, as comparative value of timer, from the edge jump interruption program of P\textsuperscript{\downarrow} first and then P\textsuperscript{\uparrow} each time; then in case of P\textsuperscript{\uparrow}, we shall clear out the value of counter and restart the counting; when the counted value is equal to the comparative value, it will enter into the timer interruption program, DSP will output the corresponding commutation logic in case of Q\textsuperscript{\downarrow} and R\textsuperscript{\uparrow}, and thus realize the fault-tolerant control of two-phase position signal of Q and R. However, during the accelerated or decelerated operation of SRM, the time interval T of position signal is varying. So we need to calculate T to obtain higher-precision time interval T.

In case of faulted position signal of all the three phases, it’s unavailable to realize fault-tolerant control since DSP cannot obtain the edge jump time of each position signal. For making the motor work normally, we may adopt the technology not requiring position sensor.
5. Experimental Verification

5.1. Fault Simulation of One-Phase Position Signal

Based on theoretical analysis, the paper has established the digital control system with TMS320F2407 DSP as the core. Here, the SRM prototype is of three-phase 12/8 structure, and has motor power 100 W, rated voltage 12 V, and rated current 20 A. In order to verify the fault analysis, fault diagnosis, and fault-tolerant control stated herein, this paper has simulated the working conditions after position signal fault during operation.

Fig. 10(a) shows the waveforms of current and position signal before fault-tolerant control when sensor P has high level fault. According to Fig. 10(a), the position signal of sensor P triggers interruption constantly, phase-A current is 0, which causes the open-phase running of motor; the total torque of system is reduced by around 1/3, and meanwhile, the torque pulse is increased obviously. As shown in Fig. 10 (b), the rotation rate of motor is reduced by around 1/3.

The waveforms of current and position signal after fault-tolerant control are as shown in Fig. 11(a). After occurrence of fault, P signal is of constantly high level. According to fault diagnosis method, DSP will detect the fault and determine fault type from the consequent falling edge interruption of sensor R (as shown in Fig. 4), and reconstruct the position signal of faulted sensor according to diagnosis result. Therefore, in Fig. 11(a), phase A lacks a current waveform, and later along with the implementation of fault-tolerant control measure, phase A will restore normal work, the waveform of current will be the same as normal one, the rotation rate of motor will remain unchanged, as shown in Fig. 11(b). Obviously, after fault-tolerant control, the reliability of system will be enhanced noticeably.

5.2. Fault Simulation of Two-Phase Position Signals

Fig. 12 (a) shows the waveforms of current and position signal before fault-tolerant control when sensors P and R have high level fault. According to Fig. 12 (a), after sensor R has high level fault, R signal doesn’t have falling edge interruption making C-phase winding ON, and phase C maintains OFF. Later, P signal has high level fault, and Phase A is always OFF. Here, the motor only has B-phase winding outputting power, and the output torque is reduced to 1/3 of rated output torque, and the rotation rate of motor is reduced by around 1/2, as shown in Fig. 12 (b). In case of operation with two phases open, the torque pulse of motor will be increased obviously, and this will possibly induce the damage of mechanical parts like bearing, etc.
The waveforms of current and position signal after fault-tolerant control are as shown in Fig. 13(a). According to the figure, DSP obtains the real-time rotor position by making use of the remained phase of position signal, and executes fault-tolerant control for the two-phase faulted position signals. The current waveforms of phases A and C are the same as that in normal condition, except for that each phase lacks one current waveform after appearance of fault (the detailed reasons are the same as that in section 5.1). According to Fig. 13(b), the rotation rate maintains constant after fault-tolerant control.

The abovementioned experiment result shows that, the theoretical analysis is accordant with the experiment result. This has proved that, the system can diagnose position signal fault in a real-time way, and carry out fault-tolerant control in time.

6. Conclusions

1) By researching position signals, this paper has brought forward the method of “real-time diagnosis of position signal fault by detecting the jump edge sequence of each phase’s position signal and the angle difference between adjacent jump edges”. The diagnosis method is easy to realize, and has relatively high dependability.

2) After real-time detection of position signal fault, the system will switch to fault-tolerant control in time, reconstruct the invalid commutation action by making use of the redundant information output by position signal detection scheme as well as the time interval T of two adjacent edge signals, and implement fault-tolerant control in time. This can improve the reliability of the system effectively.

3) The fault diagnosis method and fault-tolerant control scheme of position sensors brought forward herein have certain reference value for other brushless motor systems.

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