JPE 10-6-17

Low-Cost Fault Diagnosis Algorithm for Switch Open-Damage in BLDC Motor Drives

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Abstract

In this paper, a fault diagnosis algorithm for brushless DC (BLDC) motor drives is proposed to maintain control performance under switch open-damage. The proposed fault diagnosis algorithm consists of a simple algorithm using measured phase current information and it detects open-circuit faults based on the operating characteristic of BLDC motors. The proposed algorithm quickly recovers control performance due to its short detection time and its reconfiguration of the system topology. It can be embedded into existing BLDC drive software as a subroutine without additional sensors. The feasibility of the proposed fault diagnosis algorithm is proven by simulation and experimental results.

Key Words: Brushless DC motors, Fault diagnosis, Fault tolerant control, Reliability, Switch open-damage

I. INTRODUCTION

Brushless DC (BLDC) motors have attracted much interest due to their high efficiency, high power factor, high torque, simple control, and lower maintenance requirements. Moreover, with the development of industrial technologies, the demand for automated and large drive systems of BLDC motors in the industrial field is increasing. The reliability of BLDC motor drives is an important factor in industrial applications requiring precise operation and high performance such as powered wheelchairs, military applications, vehicles, and robot arms. Due to the need for precision and safety concerns, there is little tolerance for accidents. Therefore, there is a need for controlled systems to continue operating acceptably to fulfil specified functions following faults in the system being controlled or in the controller. A control system with this kind of fault-tolerant capability is defined as a fault-tolerant control system [1]. Fault-tolerant control has been the focus of much research. This is motivated by the need to achieve high levels of reliability, maintainability and performance in situations where the controlled systems can have potentially damaging effects on the environment if faults in its components take place. For instance, when faults in a drive system occur in the industrial field, the drive operation has to be stopped for a non-programmed maintenance schedule resulting in aditional costs which can be high. Therefore, fault-tolerance is considered to be one of the characteristics of an intelligent system. This type of system must basically perform three tasks. First, fault detection must make a binary decision to determine whether something has gone wrong or whether everything is fine. Second, fault identification determines the location of the fault, e.g., which sensor or actuator has become faulty, and estimates the size and type or nature of the fault. Third, fault isolation removes the faulty devices or part for safe operation. The relative importance of the three tasks is obviously subjective. However, detection is an absolute must for any practical system and identification is almost equally important. Fault isolation, on the other hand, whilst undoubtedly helpful, may not be essential if no reconfiguration action is involved. Hence, fault diagnosis is very often considered to be fault detection and identification.

This paper proposes a fault diagnosis algorithm for BLDC motor drives to maintain control performance under the open-circuit fault of an inverter. Open-circuit faults may result from the lifting of bonding wires due to thermic cycling, a driver failure, or a short circuit fault induced rupture of the IGBT. These faults generally do not cause system shutdowns, and are undetected by feed-back control [2],[3]. However, this may lead to secondary faults in other semiconductors, the inverter, the motor or the load since the pulsating torque and current appear under an open-circuit fault for an extended period.

There have been many papers on fault diagnosis of open-circuit faults [4]-[10]. Park's vector method [4] and the normalized DC current method [5] are accomplished by calculating the position of the current trajectory's midpoint, which is the mean value of the ac current space vector over one period. However, a BLDC motor with a trapezoidal back-EMF can be controlled without Park's transform. The phase voltage comparison method [6] and the lower switch voltage method [7] use the measurement of the voltages to quickly diagnose an open-circuit fault and to reduce the time between the fault occurrence and diagnosis. However, they need additional voltage sensors to measure the phase voltages. The wavelet-

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Manuscript received Dec. 14, 2009; revised Aug. 31, 2010

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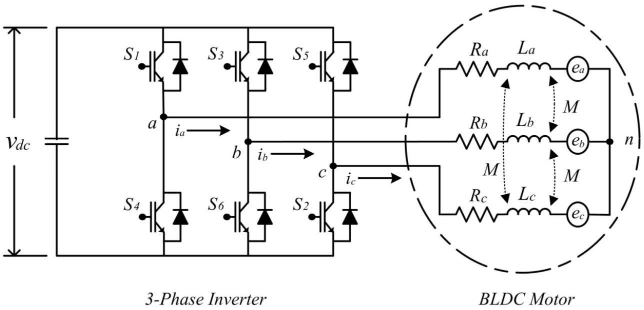


Fig. 1. Electrical equivalent circuit of BLDC motor drives.

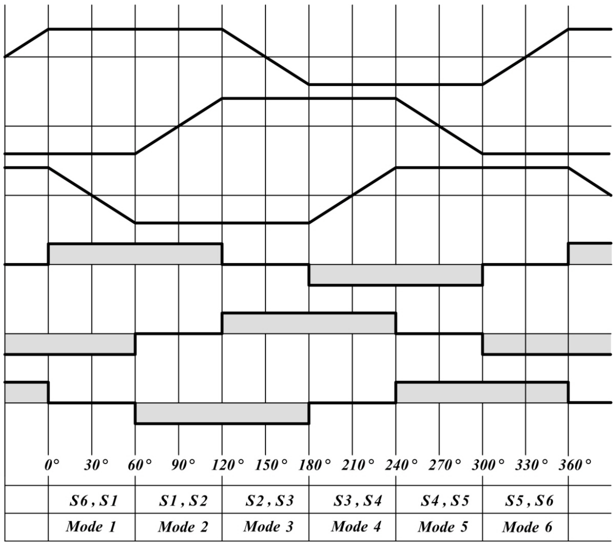


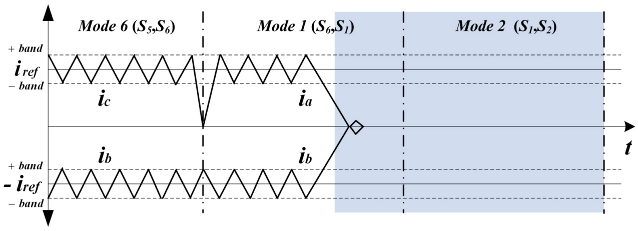
Fig. 2. Waveforms of back-EMFs, phase currents.

fuzzy algorithm [8] and the wavelet-neural network method [9] use wavelet analysis to detect fault signatures. The wavelet transform is an emerging DSP algorithm that has variable time and frequency resolutions. However, these expert systems require a relatively high computing process. A comparison method between the measured and predicted currents for the fault condition [10] detects a torque output that is reduced to 4/6 of that available from a current controlled healthy drive at a given speed.

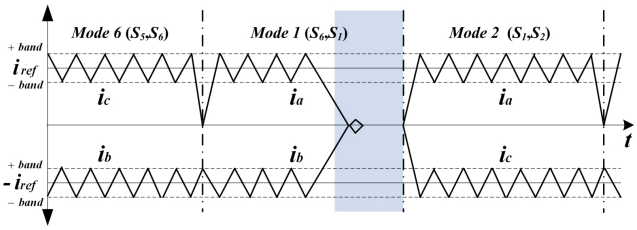
paper proposes a low-cost fault diagnosis algorithm for switch open-damage of BLDC motor drives. The proposed algorithm is achieved without adding additional sensors and by a simple algorithm that uses the operating characteristic of a BLDC motor drive. It can be embedded into an existing BLDC motor drive system as a subroutine without excessive computational effort. To validate the reliability of this algorithm, the existing isolation and reconfiguration methods [11], [12] are integrated. The feasibility of the proposed fault diagnosis algorithm is verified by simulation and experiment results.

II. ANALYSIS FOR SWITCH OPEN-DAMAGE OF BLDC MOTOR DRIVES

The electrical equivalent circuit of this system is shown in Fig. 1. Generally, a BLDC motor drive system can be modeled as an electrical equivalent circuit that consists of a resistance, an inductance and a back-EMF per phase. As shown in Fig. 2, the BLDC motor, which has a trapezoid-shaped back-EMF, is operated by exciting two of the three phases. Only two switches are operated in one mode. The proposed fault diagnosis algorithm is achieved by using the characteristics of the phase currents in BLDC motor drives. When an open-circuit fault of the switch occurs, the current waveform appears different depending on the position of the faulty switch.



(a) Switch open-damage of *S1*



(b) Switch open-damage of *S6*

Fig. 3. Current waveforms under open-circuit faults in *Mode 1.*

For comprehension of an open-circuit fault of a switch, Fig. 3 shows the waveforms of the two phase currents in the cases of a open-circuit fault of the upper switch (S_1) and the lower switch (S_6) in *Mode 1.*

A. Upper Switch (S_1) Open-Damage in Mode 1

As shown in Fig. 3(a), when an open-circuit fault of the upper switch (S_1) occurs in *Mode 1*, even if the lower switch (S_6) operates normally, the currents of phases A and B do not flow through the motor windings. Moreover, when the lower switch (S_2) is normally operated by the switching pattern in *Mode 2*, the currents of phases A and C also do not flow due to the open-circuit fault of the upper switch (S_1). As a result, if an open-circuit fault of the upper switch (S_1) occurs in *Mode 1*, the phase currents do not flow in *Mode 1* and *Mode 2*.

B. Lower Switch (S_6) Open-Damage in Mode 1

As shown in Fig. 3(b), when an open-circuit fault of the lower switch (S_6) occurs in *Mode 1*, even if the upper switch (S_1) operates normally, the phase currents of phases A and B do not flow thorough the motor windings. However, when the lower switch (S_2) is normally operated by the switching pattern in *Mode 2*, the currents of phases A and C can flow despite the open-circuit fault of the lower switch (S_6). As a result, S_1 and S_2 operate normally in *Mode 2*, even if an open-circuit fault of the lower switch (S_6) occurs in *Mode 1.*

III. PROPOSED FAULT DIAGNOSIS ALGORITHM

The operation of a BLDC motor drive system is classified into six-modes by the switching pattern. The current waveforms are different depending on the state of each mode. The

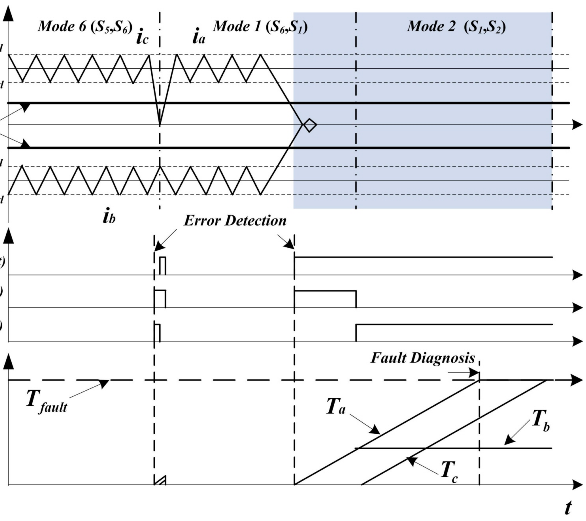


Fig. 4. Process of the proposed fault diagnosis algorithm.

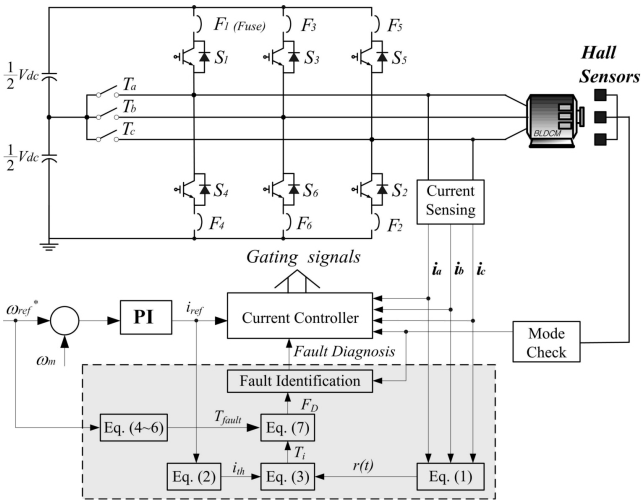


Fig. 5. Overall structure of the proposed fault diagnosis.

characteristics of current waveforms offer a simple algorithm to diagnose an open-circuit fault. The fault diagnosis algorithm uses a fault flag (F_D) that represent the fault diagnosis. The hysteresis current controller generates switching signals for the phase currents to follow the reference current calculated by the speed controller.

The residual for the fault detection of each phase is defined as:

$$r_i(t) = \left\| i_{ref} - i_i \right\| \quad (i = a,b,c). \tag{1}$$

The threshold value is determined in order to judge whether or not an error occurs. The decided threshold value is given by:

$$i_{th} = g_f \cdot i_{ref} \tag{2}$$

where g_f is selected between 0 and 1 to minimize the possibility of false alarms in the event of noise or changes in the operating point.

After an open-circuit fault of the switches, the residual between the reference and the actual currents increases because the actual current cannot follow the reference current. This residual can be used to detect errors according to a simple threshold logic:

$$\begin{cases} \|r_i(t)\| & > & i_{th}(Threshold) & \text{nomal} \\ \|r_i(t)\| & < & i_{th}(Threshold) & \text{error} \end{cases} . \tag{3}$$

When the residual is less than the decided threshold value (i_{th}), an error is detected. The others judge by normal operation. Because a BLDC motor drive is operated by a square-wave current controller, the phase current of a BLDC motor is changed according to the rotor speed and the load variations. Therefore, it is necessary to provide sufficient robustness not only in the residual generation but also in fault detection. The proposed fault diagnosis algorithm needs to define the fault detection time, which is calculated by a reference speed. The relation between the frequency, f, of the induced voltage in cycles per second and the mechanical speed, N_{ref}, in revolutions per minute, can be shown as:

$$f = \frac{\omega_e}{2\pi} = \frac{P}{2}\frac{N_{ref}}{60}. \tag{4}$$

A BLDC motor drive is operated by switching pattern that consists of six modes per cycle. The time per mode (t_M) is calculated by:

$$t_M = \frac{1}{f} \times \frac{1}{N_M} \tag{5}$$

where N_M is the number of modes per a cycle. The fault detection time (T_{fault}) is defined by:

$$T_{fault} = k_f \times t_M \tag{6}$$

where k_f, which is the sensitivity factor for faults, which is selected to be between 1 and 2.

If $k_f > 2$, the fault may be not detected. Also, if k_f is too low, the probability of false a alarm increases. Therefore, the selection of k_f is a compromise between fast fault detection and stable fault detection.

The algorithm for fault detection and diagnosis is given by:

$$\begin{cases} F_D = 1 & if\ T_{fault} > T_{a,b,c} \\ F_D = 0 & if\ T_{fault} < T_{a,b,c} \end{cases} \tag{7}$$

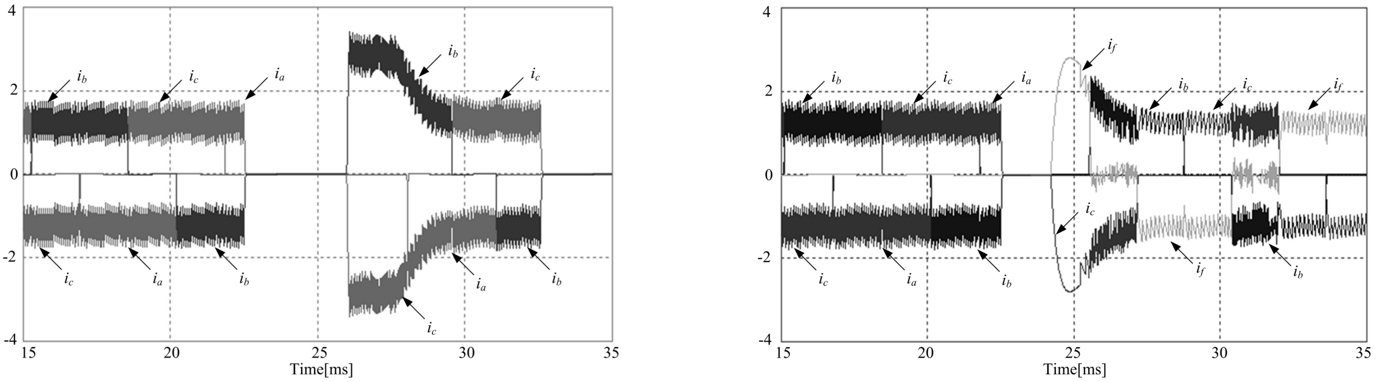
where T_a, T_b and T_c are the error times for each phase detecting the error continuously.

As shown in Fig. 4, if the error time ($T_{a,b,c}$) for detecting the error continuously is longer than the fault detection time (T_{fault}), the fault flag (F_D) for a faulty diagnosis changes from low to high. After the open-circuit fault of a switch, the error time of the faulty phase reaches earlier than the other phase by the fault detection time.

TABLE I
MOTOR SPECIFICATIONS

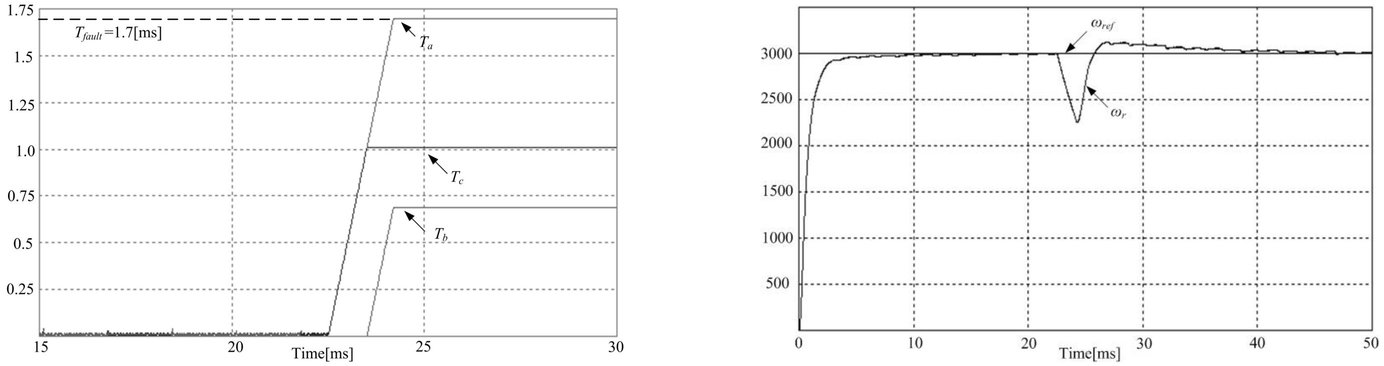
Rated power	250 W
Rated Voltage	24 V
Rated torque	0.662 N·m
Rated speed	3000 rpm
Number of pole-pairs	8
Back-EMF Constant	5 V/krpm

Consequently, a faulty phase can be identified by a comparison of the error times for the three phases after the fault. The fault detection time for fault identification must be longer than the interval of a mode because the error times of the two



(a) Faulty current waveforms

(b) Current waveforms by fault tolerant control



(c) Error times for three phase and Fault detection time

(d) Rotor speed

Fig. 6. Simulation results of the proposed method.

excited phases increase identically within a mode. Therefore, the sensitivity factor for fault identification is defined within the range of $1 < k_f < 2$. This method cannot avoid decreases in control performance until the fault identification. However, this method can be embedded into existing BLDC motor drive software at a low cost.

IV. OVERALL FAULT TOLERANT SYSTEM WITH THE PROPOSED FAULT DIAGNOSIS ALGORITHM

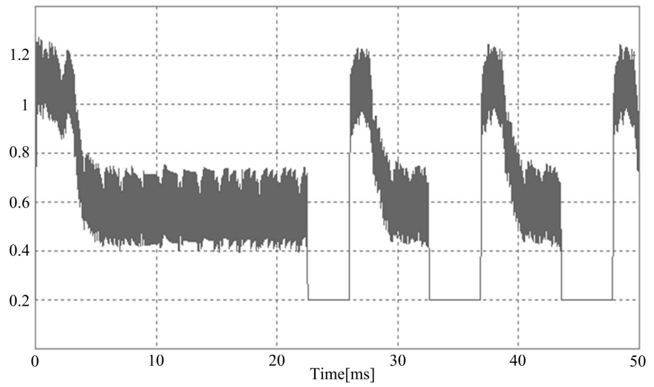
An overall fault tolerant system structure with the isolation of a faulty phase is shown in Fig. 5. The existing isolation and reconfiguration method is introduced to validate the feasibility of the proposed algorithm. When an open-circuit fault of a switch is identified, the bidirectional switch of the faulty phase is fired in order to connect the faulty phase to the midpoint of the DC-link. At the same time the switching signals of the faulty phase are removed. The system reconfiguration after isolating the faulty phase consists of a FSTP inverter for BLDC motor drives [12]. Because this control scheme has irregular voltage utilization, during the half DC-link voltage period, the rate of current incensement is lower than during the full DC-link voltage period. Although the fault tolerant control shows reduced performances and a short working time under fault, this aspect is considered as a compromise. In the case of a short-circuit fault of a switch, the applied fast active fuses blow out immediately. The short-circuit fault is then judged to be an open-circuit fault by the fault diagnosis algorithm.

V. SIMULATION RESULTS

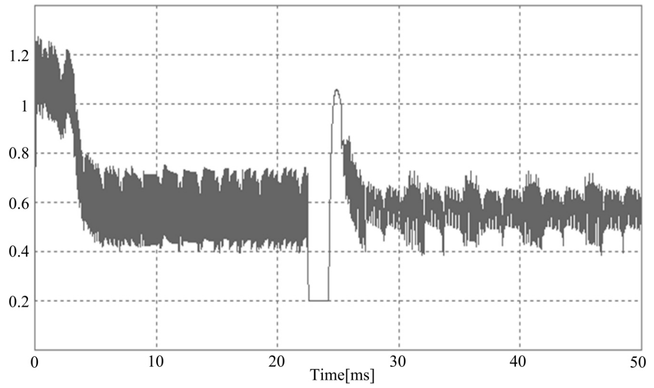
Simulations were performed on the BLDC motor which has the parameter ratings in Table I. In this work, only an open-circuit fault of switch (S_1) was considered in *Mode 1*. Also, the effect of this type of fault in any other devices is assumed to be symmetrical. Fig. 6 shows the simulation results for the proposed fault diagnosis algorithm when an open fault of the upper switch (S_1) occurs in *Mode 1*.

An open fault occurs at 22.5ms. Fig. 6(a) shows the current waveforms of three phases without fault tolerant control. After the fault, current waveforms of i_a and i_b do not appear in *Mode 1* or *Mode 2*. Fig. 6(b) shows the current waveforms with the fault diagnosis algorithm. After the fault identification, the faulty phase is promptly disconnected by removing the switching signals. Consequently, i_a suddenly drops to zero, while a neutral current (i_f) begins to flow by the bidirectional switch, with i_b and i_c. Fig. 6(c) shows the error times for fault detection. After a fault, the fastest phase which the error time reaches the fault detection time is phase A. In this method, the fault detection time is t = 1.7 ms longer than the interval of a mode. Fig. 6(d) shows the rotor speed. After a fault, the rotor speed decreases by 2500 rpm due to the open fault of the upper switch (S_1) in *Mode 1*. However, with the fault tolerant control, the actual rotor speed can follow the reference speed well. Fig. 7 represents the developed torque of the BLDC motor with and without the fault tolerant control.

In Fig. 7(a), it can be seen that the developed torque without



(a) Faulty operation



(b) Fault tolerant operation.

Fig. 7. Developed torque of the BLDC motor.

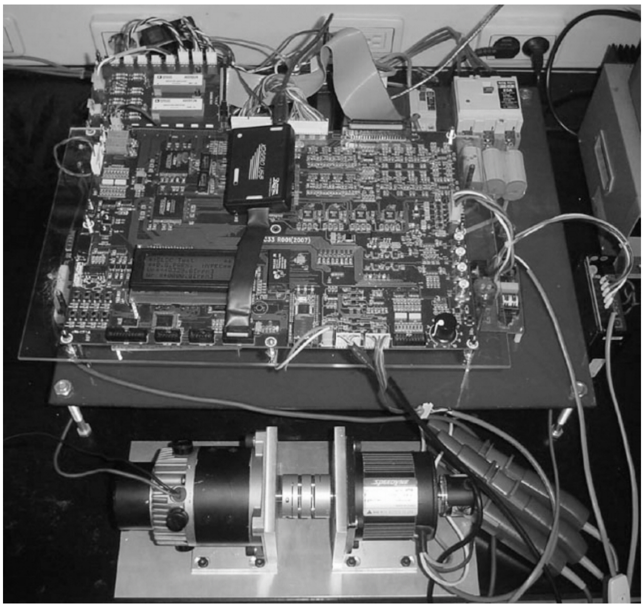


Fig. 8. Photograph of the laboratory prototype.

fault tolerant control has a torque ripple continuously under an open-circuit fault. In Fig. 7(b), the constant developed torque after a fault diagnosis is represented by the fault tolerant control, which protects the system from secondary faults with a pulsating torque.

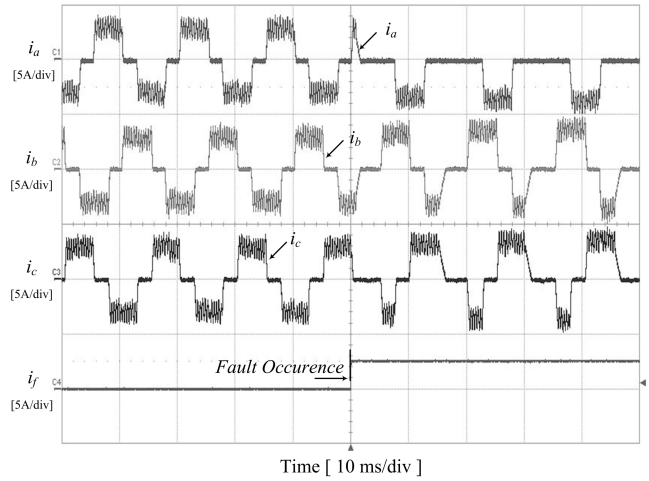


Fig. 9. Experimental results without the fault tolerant control.

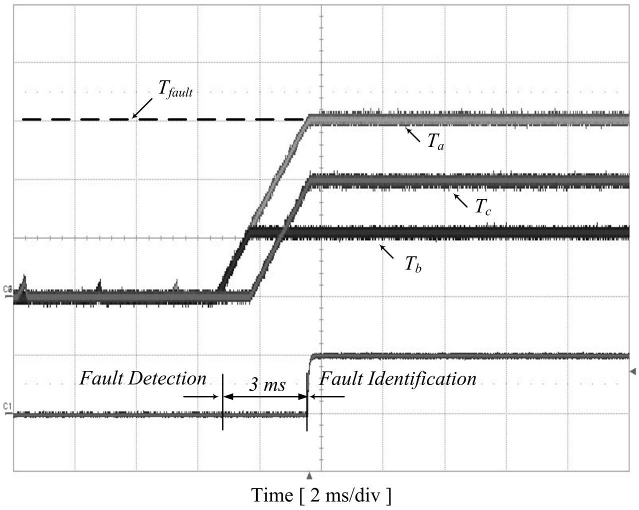


Fig. 10. Experimental waveforms for the error times of three phases and fault identification signal.

VI. EXPERIMENTAL RESULTS

In order to verify the proposed fault diagnosis algorithm, an experiment was performed using the designed laboratory prototype shown in Fig. 8. The main controller was configured by using a (DSP) TMS320VC33. The sampling time in the control algorithm was 50s. The inverter used in the experiment was implemented with a (IPM) PM30CSJ060 devices. A 250W BLDC motor was coupled with the laboratory prototype in order to test the proposed fault diagnosis algorithm. In this work, an open-circuit fault of switch (S_1) was enduced by the enforced off-signal of the gate driver. Fig. 9 shows the current waveforms of three phases without the fault tolerant control. After the fault, the current waveforms of i_a and i_b do not appear in *Mode 1* or *Mode 2*.

Fig. 10 shows the error times of the three phases and the fault identification signal. After the fault, the fastest phase which the error time reaches the fault detection time T_{fault} is phase A. The fault detection time is 3ms which is longer than the interval of a mode (2.5ms). Fig. 11 shows the phase current i_a, the error time, and the fault system signals. After a fault occurrence, i_a drop below the threshold value and the error

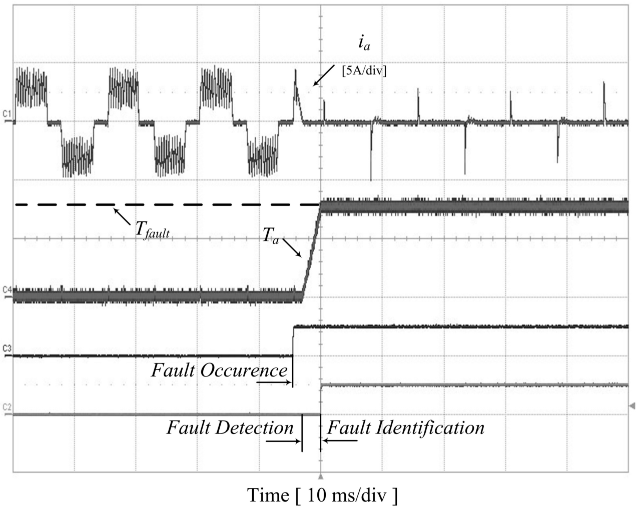


Fig. 11. Experimental waveforms of phase current i_a, the error time, and fault system signals.

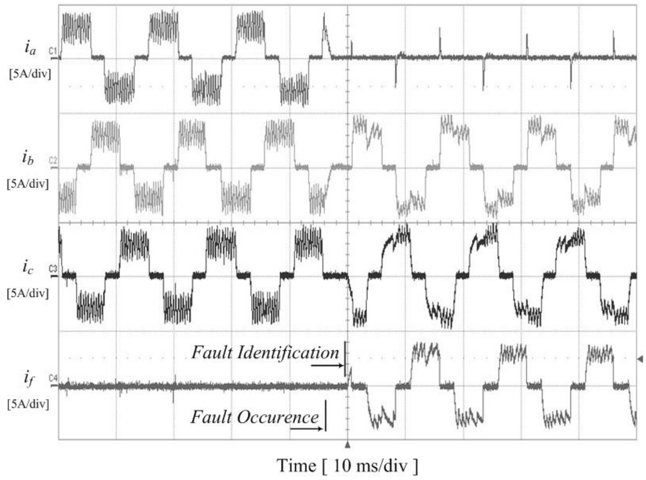


Fig. 12. Experimental results for phase currents i_a, i_b, i_c and i_f with the fault tolerant control.

time of phase *A* increases. When the error time was longer than the fault detection time, fault diagnosis was achieved. Fig. 12 shows current waveforms of the proposed method when an open-circuit fault of the upper switch (S_1) occurs in *Mode 1*. When the sensitivity factor k_f for faults was set to1.2, the fault detection time (T_{fault}) at the reference speed ($\omega_{ref} = 2000$ r/min) is 3ms. As shown in Fig. 12, a faulty phase is promptly disconnected by removing the switching signals after fault identification. Consequently, current i_a suddenly drops to zero, while a neutral current i_f begins to flow by a bidirectional switch, with i_b and i_c.

VII. CONCLUSIONS

In this paper, a low-cost fault diagnosis algorithm was investigated to improve the reliability of BLDC motor drive systems. The proposed algorithm was achieved based on the operating characteristics of a BLDC motor and it quickly recovers the control performance with a fast fault detection time and a reconfiguration of the system topology. It then is available to drive in continuous operation under the fault. In comparison to the existing fault diagnosis, the proposed algorithm can simply identify a fault condition without additional sensors for fault detection and identification. Simulation and experimental results confirm the feasibility of the proposed drive system for continuous operation under a fault condition. In addition, when the proposed fault diagnosis is applied to existing BLDC motor drives, the reliability and robustness of the BLDC motor drive system can be improved with a low cost.

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