EKF-Based Fault Diagnosis for Open-Phase Faults of PMSM Drives

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***Abstract*-The reliability of PMSM drives has been dealt with an important factor in industrial applications requiring a precise operation and high-performance. This paper proposes the fault diagnosis for open-phase faults of PMSM drives using an Extended Kalman Filter (EKF) and DC-link current information. The proposed fault diagnosis can be achieved without additional devices and distinguish where the open-phase fault occurs between PMSM and power electronic equipment. the feasibility of the proposed fault diagnosis scheme is proved by Simulation results.**

I. Introduction

Permanent magnet synchronous motors (PMSMs) are widely used in many applications such as electrical vehicles, appliances, aircraft, and industrial servo drives. The reliability of PMSM drives has been dealt with an important factor in industrial applications requiring precise operation and high performance. There are many diverse faults occurred in PMSM drives. Electrical faults of PMSM drives are frequently occurred in PMSM and power electronics equipment connected to the PMSM. Faults in a PMSM are resulted from open and short phase faults of stator windings, rotor faults, or bearing faults. Faults in power electronics equipment are occurred by open-circuit and short-circuit faults in power devices and connection wires. The reliability of PMSM drives can be improved by the development of fault diagnosis schemes for these faults. In recent years, many different fault diagnosis schemes have been developed and published in papers. Several papers for faults in PMSM drives have been published for the following fault types: rotor faults[1-3] and stator faults[4-5] in PMSM, and open-circuit faults[6] and short-circuit faults[7] in an inverter.

This paper proposes the fault diagnosis for open-phase faults of PMSM drives using an Extended Kalman Filter (EKF) and DC-link current information. Stator resistances of PMSM are estimated by the EKF in real time. If an open-phase fault occurs, the stator resistance of a faulty phase estimated by the EKF is rapidly changed. And then, the open-phase fault is identified by comparing the estimated DC-link current by switching states with the measured DC-link current by a current sensor. The proposed fault diagnosis scheme at next Sector of voltage vector

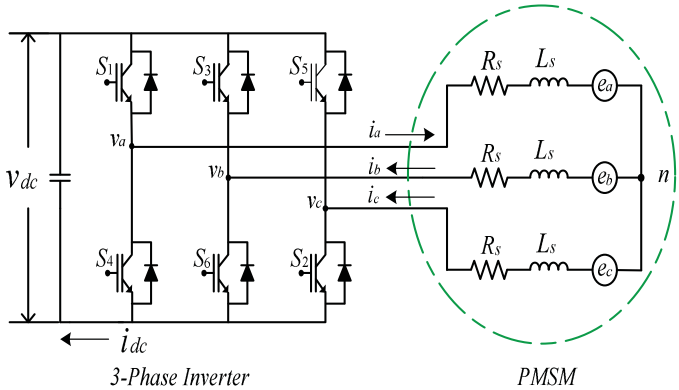

Fig. 1. The electrical equivalent circuit of PMSM drives.

defines where the open-phase fault occurs between PMSM and the switch of an inverter. The proposed fault diagnosis can be achieved without additional devices and distinguish where the open-phase fault occurs between PMSM and power electronic equipment.

In this paper, the fault is considered to the open-phase fault in switches of an inverter or phases of a motor. Also, the considered faults affect a phase only. The feasibility of the proposed fault diagnosis scheme is proved by simulation results.

II. PMSM Model for Fault Detection

As shown in Fig. 1, PMSM drives can be modeled as an electrical equivalent circuit that consists of a resistance, an inductance and back-EMF per a phase. The PMSM model used in an EKF algorithm can be based on either a stationary frame or a synchronous rotating frame. Voltage and current equations in the stationary frame can be given by

$$\begin{aligned} \frac{d}{dt} i_\alpha &= -\frac{R_s}{L_s} i_\alpha - \frac{e_\alpha}{L_s} + \frac{v_\alpha}{L_s} \\ \frac{d}{dt} i_\beta &= -\frac{R_s}{L_s} i_\beta - \frac{e_\beta}{L_s} + \frac{v_\beta}{L_s} \end{aligned} \tag{1}$$

where i_α, i_β, e_α, e_β, v_α, and v_β are represent the current, the back-EMF, and the excitation-voltage components, respectively; R_s and L_s are the stator resistance and inductance, respectively.

In order to estimate the variation of the stator resistance, Eq. (1) can be expressed as (2).

$$\frac{d}{dt}\begin{bmatrix} i_\alpha \\ R_s \end{bmatrix} = \frac{1}{L_s}\begin{bmatrix} -R_s & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} i_\alpha \\ R_s \end{bmatrix} + \frac{1}{L_s}\begin{bmatrix} 1 \\ 0 \end{bmatrix}\left[v_\alpha + \lambda_f \omega_r \sin\theta\right] \tag{2}$$

The dynamic model of the machine in state-variable form can be expressed as

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) \end{aligned} \tag{3}$$

where $x(t) = [i_\alpha \;\; R_s]^T$ is a state vector, $u(t) = [v_\alpha + \lambda_f \omega_r \sin\theta]$ is a input vector, $y(t) = [R_s]$ is a output vector and matrices A, B and C are given by

$$A = \begin{bmatrix} -\dfrac{R_s}{L_s} & 0 \\ 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} \dfrac{1}{L_s} \\ 0 \end{bmatrix} \quad C = \begin{bmatrix} 0 & 1 \end{bmatrix} \tag{4}$$

III. Extended Kalman Filter Algorithm

For digital implementation of an EKF, the model must be discretized as the following form:

$$\begin{aligned} x(k+1) &= F(k)x(k) + G(k)u(k) \\ y(k) &= H(k)x(k) \end{aligned} \tag{5}$$

where $F(k) = I + A \cdot Ts$, $G(k) = B \cdot Ts$, $H(k) = C$.

Nonlinear discrete models with white noise are given by

$$\begin{aligned} x(k+1) &= f(x(k),\; u(k)) + w(k) \\ y(k) &= hx(k) + v(k) \end{aligned} \tag{6}$$

where $w(k)$ and $v(k)$ are system noise vector and measurement noise with covariance Q and R, respectively. The overall structure of the EKF is well-known by employing two step prediction and correction algorithm.

Time update (predict) step:

$$\begin{aligned} \hat{x}(k+1|k) &= F(k)\hat{x}(k|k) + u(k) \\ P(k+1|k) &= F(k)P(k|k)F^T(k) + Q(k) \end{aligned} \tag{7}$$

Measurement update (correct) step:

$$\begin{aligned} K(k+1) &= P(k+1)H^T(k+1) \\ &\quad \times \left[H(k+1)P(k+1|k)H^T(k+1) + R(K+1)\right]^{-1} \\ \hat{x}(k+1|k+1) &= \hat{x}(k+1|k) \\ &\quad + K(k+1)\left[y(k+1) - H(k+1)\hat{x}(k+1|k)\right] \\ P(k+1|K+1) &= \left[I - K(k+1)H(k+1)\right]P(k+1|k) \end{aligned} \tag{8}$$

where P is covariance matrix, K is kalman gain. The $(k+k|k)$ denotes the predicted estimate: i.e. the present process is estimated by the previous step. Accordingly, the $(k+1|k+1)$ represents the present estimate.

IV. Proposed Fault Diagnosis Scheme

A. Fault Detection using EKF

Stator resistances of PMSM are estimated by the EKF in real time. Generally, the stator resistance of PMSM is changed by the variation of temperature. A variation in the stator temperature can cause a significant variation in the stator resistance. However, the stator resistance under normal condition is determined by the temperature dependence, which is given by

$$R = R_0(1 + \alpha\Delta T) \tag{9}$$

where R_0 is resistance at reference temperature T_0=25°C , α is resistance temperature coefficient, and ΔT is temperature increase.

If an open-phase fault occurs, the stator resistance of a faulty phase estimated by the EKF is rapidly changed in compared with the stator resistance varied by temperature. Therefore, the open-phase fault is easily detected by using EKF.

B. Fault Identification using DC-link Current Information

The fault identification is achieved by using DC-link current information. It is well known that it is possible to determine the phase current in the three phases by a dc-link current sensing [8]. In state V_1 (100) as shown in Fig. 2, phase A is connected to the positive bus and the B and C phases are tied to the negative bus. Under the normal condition, the current i_a of phase A flows through the positive bus and must return via the negative bus; thus $i_{dc} = i_a$. State V_4 (011) is the complement of state V_1 (100). In this case i_{dc} is same as $-i_a$ under the normal condition. From the symmetry of the system it is appreciated that i_{dc} depends on only i_b in states V_3 (010) and V_6 (101), and i_{dc} current represents i_c in states V_5 (001) and V_2 (110). Table I shows the relationship between the active voltage vectors and the actual dc-link current. As shown in Fig. 2, states $V_{1\text{-}6}$ can be identified from the six switch-control signals fed to the inverter. Hence, the value of each phase current can be extracted from a DC-link current sensor at the appropriate time. After the fault detection, the

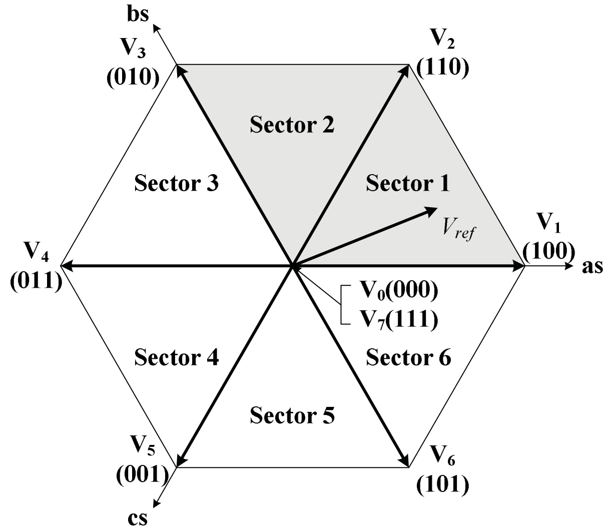

Fig. 2. Space vector modulation.

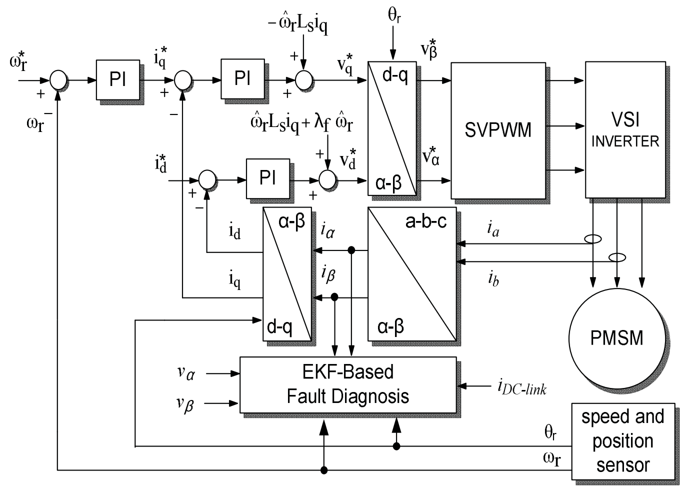

Fig. 3. Block diagram of the proposed EKF-based fault diagnosis.

TABLE I
RELATIONSHIP BETWEEN VOLTAGE VECTORS AND THE ACTUAL DC-LINK CURRENT

Voltage Vector	DC-link current i_{dc}
V_1(100)	i_a
V_2(110)	$- i_c$
V_3(010)	i_b
V_4(011)	$- i_a$
V_5(001)	i_c
V_6(101)	$- i_b$
V_0(000) and V_7(111)	0

TABLE II
SPECIFICATION OF PMSM USED IN SIMULATION

Parameters	Symbols	Values
Number of pole pairs	N_p	4 pole
Stator resistance	R_s	3.8 Ω
Synchronous inductance	L_s	0.027 H
Flux linkage	λ_f	0.1 V·s
Rotor inertia	J	0.0007 kg·m^2
Friction constant	B	0.0001 N·m/rad/s

proposed fault identification can distinguish where the open-phase fault occurs between PMSM and power electronic equipment. For example, if the open-phase fault occurs at switch S_1 in Sector 1, the current i_a of phase A decreases to zero because the positive bus is opened. The DC-link current is different from the value under normal condition. The DC-link current at state V_1 may be zero under faulty condition and that at state V_2 is same as i_b and $-i_c$. If the open-phase fault occurs in a motor, the current of faulty phase does not flow through the motor after two sectors. After the fault detection, the current of faulty phase does not appear, the fault diagnosis scheme can identify the open-phase fault of the motor. And then, the strategy consists in reformulating the current references so that the rotating MMF generated by the armature currents do not change, even if one phase is open-circuited after a fault occurrence[9]. However, If the open-phase fault occurs in an inverter, the reconfiguration achieved by isolating and disconnecting the faulty switch has been proposed in [10], [11]. The choice between two configurations depends on the application interests because these methods have individual merits related the capability of devices, the cost, the operating time after faults. Fig. 3 shows the Block diagram of the proposed EKF-based fault diagnosis.

V. SIMULATION RESULTS

Simulations are performed by using Mathlab/Simulink simulator to prove the feasibility of the proposed algorithm. The specification of the PMSM is as Table II. Figs. 4 and 5 present the simulation results according to different fault conditions. The open-phase fault of phase A in Sector 1 identically occurs at 0.3[s]. Fig. 4 shows Simulation results under the open-phase fault of the upper switch S_1. As shown in Fig. 4(a), the DC-link current is equal to three phase currents by switching states. After the open-phase fault of S_1, the DC-link current is different from the value under normal condition. The stator resistance estimated by the proposed fault diagnosis scheme suddenly increases in Fig. 4(b). The open-phase fault is detected by this changed value in Fig. 4(b). After the fault detection, the open-

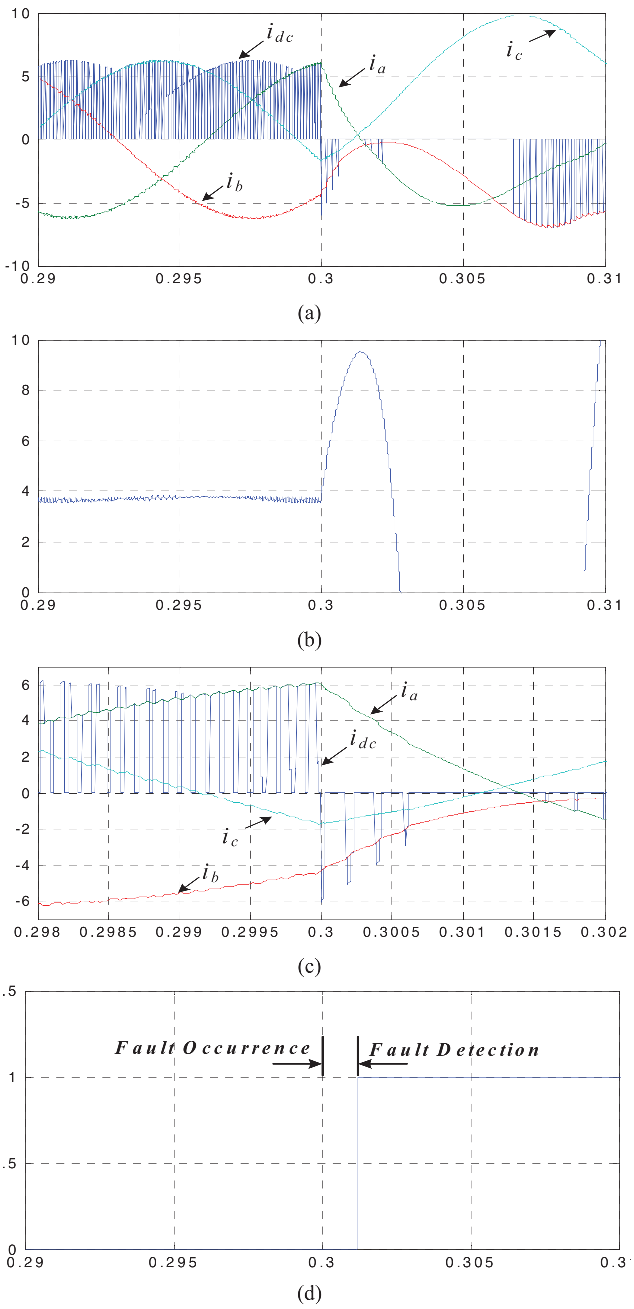

Fig. 4. Simulation results under the open-phase fault of S_1 in Sector 1. (a) current waveforms. (b) Estimated stator resistance. (c) Extended current waveforms. (d) Fault detection signal of phase A.

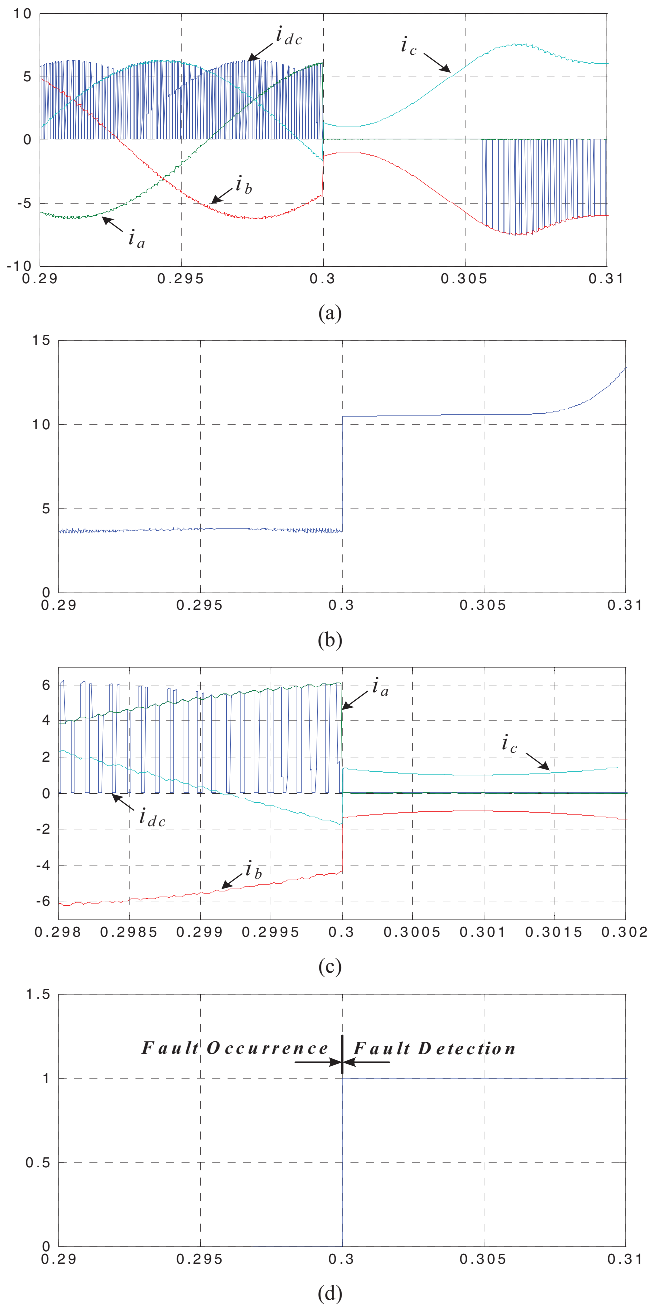

Fig. 5. Simulation results under the open-phase fault of the PMSM in Sector 1. (a) Current waveforms. (b) Estimated stator resistance. (c) Extended current waveforms. (d) Fault detection signal of phase A.

phase fault is identified by comparing the estimated DC-link current by switching states with the measured DC-link current by a current sensor as shown in Fig. 4(c). Fig. 4(d) shows the fault detection signal of phase A. Fig. 5 shows Simulation results under the open-phase fault of the PMSM. As shown in Fig. 5(a), the DC-link current is equal to three phase currents by switching states. After the open-phase fault of the PMSM, the current of faulty phase and the DC-link current do not flow through the motor. the DC-link current is different from the value under normal condition. The estimated stator resistance increases faster than the open-phase fault of switch S_1 in Fig. 5(b). Therefore, the open-phase fault of the PMSM is rapidly detected.

VI. Conclusion

This paper proposes the fault diagnosis for open-phase faults of PMSM drives using an Extended Kalman Filter (EKF) and

DC-link current information. The EKF are used to estimate stator resistances of PMSM in real time. After fault detection, the open-phase fault is identified by comparing the calculated DC-link current by switching states with the measured DC-link current by a current sensor. The proposed fault diagnosis scheme can be achieved without additional devices and distinguish where the open-phase fault occurs between PMSM and power electronic equipment. The feasibility of the proposed fault diagnosis is proved by simulation results.

ACKNOWLEDGMENT

This research was supported by a grant from Railroad Technology Development Program (RTDP) funded by Ministry of Land, Transport and Maritime Affairs of Korean government.

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