Fault Diagnosis for Open-Phase Faults of Permanent Magnet Synchronous Motor Drives Using Extended Kalman Filter

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***Abstract* - The reliability of the PMSM drives is the one of critical factors in several industries, in particularly, the areas where the precise operation and/or high performance are required. This paper proposes a novel diagnosis scheme using Extend Kalman Filter (EKF), especially, in subject to the open-phase faults of the inverter switches. The stator resistances of PMSM are estimated by the EKF in real time. The proposed diagnosis scheme is implemented without any extra devices. Moreover, since it uses a simple algorithm by analyzing only estimated stator resistances of each phase, the detection speed becomes fast. The feasibility of the proposed fault diagnosis scheme is proved by several simulation and experimental results.**

I. INTRODUCTION

A permanent magnet synchronous motor (PMSM) has been widely used in various applications including electrical vehicles, appliances, aircraft, and industrial servo drives due to its high power density and large torque to inertia ratio [1], while improvements in the properties of permanent-magnet materials have increased their viability. The reliability of the PMSM drives is the one of critical factors in several industries, in particularly, the areas where the precise operation and/or high performance are required. In these areas, a sudden drive failure results in serious damages and economical losses.

In order to increase a fault-tolerance, the drive system should be capable for three tasks; (a) a fault detection should make a binary decision to determine whether something has gone wrong or whether everything has been fine. (b) a 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. (c) a fault isolation removes the faulty devices and part for safety operation. Determining a priority of these three tasks is very dependent on the given design specifications or requirements. The fault detection, however, usually has the highest priority among three tasks. In some applications, the fault isolation has similar priority as the fault detection. The fault identification is often considered to be less important than them unless reconfiguration action is required. In simple words, a fault diagnosis is often considered as the fault detection and identification.

Several kinds of the fault occur in the PMSM systems. The most frequent one has been known as the electrical fault of the PMSM, such as the open or short circuit of stator or rotor windings and bearing faults [2]-[6]. Power electronics has also been considered as weak equipment. The frequent failure usually originates from the open or short circuit in either power devices or wire connection.

In recent years, several papers for faults in motor drive system have been published using the following schemes: fault detection and identification methods [2]-[7] and fault tolerant schemes [3],[4]. However, most existing fault detection and identification methods have problems because the fault detection time takes at least one fundamental period, the process for detecting the fault is complex, and schemes to identify the fault are inadequate. Moreover, this methods use additional sensor for fault diagnosis. To solve these problems in the novel proposed fault diagnosis, it is possible to detect and identify the fault having a single algorithm.

This paper proposes a novel diagnosis scheme using Extended Kalman Filter (EKF), especially, in subject to the open-phase fault of the inverter switches. The 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. This characteristic of the stator resistance offer a simple algorithm to detect open-phase fault. The proposed diagnosis scheme is implemented without any extra devices. Moreover, since it uses a simple algorithm by analyzing only estimated stator resistances of each phase, the detection speed becomes fast. The feasibility of the proposed fault diagnosis scheme is proved by several simulation and experimental results.

II. PMSM MODEL FOR FAULT DETECTION

Generally, the PMSM drive system can be modeled as an electrical equivalent circuit that consists of a resistance, an inductance, and back-EMF per a phase. The electrical equivalent circuit of this system is shown in Fig. 1. Although the conventional d-q motor model obtained through the transformation of phase voltage model is widely us

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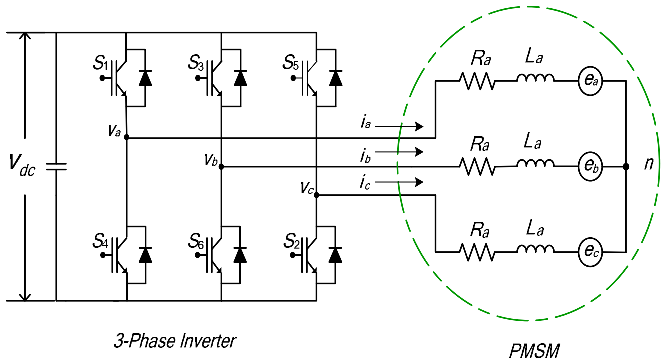

Fig. 1. The electrical equivalent circuit of PMSM drives.

analyze and control AC motor, it cannot be used under open faults in switching devices since 3-phase balanced condition is no longer hold under the open fault and it is not easy to obtain motor input voltage in open phase from the pole voltage. Therefore, in the normal condition without faulty, the dynamic model of 3-phase balanced PMSM is written as

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_a & 0 & 0 \\ 0 & L_b & 0 \\ 0 & 0 & L_c \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

where i_a, i_b, and i_c are phases currents. v_a, v_b, and v_c are three-phase terminal voltages. e_a, e_b, and e_c are phase back-EMFs. R and L are resistance and inductance of a phase windings.

The phase back-EMFs (e_a, e_b, and e_c) can be approximately expressed as:

$$\begin{aligned} e_a &= w_r \lambda_f \cos\theta_r \\ e_b &= w_r \lambda_f \cos(\theta_r - 2\pi/3) \\ e_c &= w_r \lambda_f \cos(\theta_r + 2\pi/3) \end{aligned} \quad (2)$$

where λ_f, ω_r, and θ_r represent flux linkage of permanent magnet, rotor speed in electrical rad/s, and rotor position in electrical rad.

Eq. (3) is derived from (1). This mathematical equation of a PMSM model is applied to EKF algorithm.

$$\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{L_a} & 0 & 0 \\ 0 & -\frac{R_b}{L_b} & 0 \\ 0 & 0 & -\frac{R_c}{L_c} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} \\ \frac{1}{L_b} \\ \frac{1}{L_c} \end{bmatrix} \begin{bmatrix} v_a - e_a \\ v_b - e_b \\ v_c - e_c \end{bmatrix} \quad (3)$$

III. Proposed Fault Diagnosis Scheme

A. Extended Kalman Filter Algorithm

The EKF is currently one of the most sophisticated methods of identification of the machine parameters. The detail derivation of the EKF equations can be found e.g. in [7], [8]. If stator resistance variation is considered negligible, dR/dt=0. In order to estimate the variation of the stator resistance, Eq. (4) can be expressed as (3).

$$\frac{d}{dt}\begin{bmatrix} i_j \\ R_j \end{bmatrix} = \begin{bmatrix} -\frac{R_j}{2L_j} & -\frac{i_j}{2L_j} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} i_j \\ R_j \end{bmatrix} + \begin{bmatrix} \frac{1}{L_j} \\ 0 \end{bmatrix} \begin{bmatrix} v_j - e_j \end{bmatrix} \quad (4)$$

$$(j = a, b, c)$$

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

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) \end{aligned} \quad (5)$$

where $x(t) = [i_j \ R_j]^T$ is a state vector, $u(t) = [v_j\text{-}e_j]$ is a input vector, $y(t) = [1 \ 0]$ is a output vector and matrices A, B and C are given by

$$A = \begin{bmatrix} -\frac{R_j}{2L_j} & -\frac{i_j}{2L_j} \\ 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} \frac{1}{L_j} \\ 0 \end{bmatrix}$$
$$C = \begin{bmatrix} 1 & 0 \end{bmatrix} \quad (6)$$

For digital implementation of an EKF, the time-discrete state-space model of the PMSM can be obtained from (6) as follows:

$$\begin{aligned} x(k+1) &= F(k)x(k) + G(k)u(k) \\ y(k) &= H(k)x(k) \end{aligned} \quad (7)$$

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

$$\begin{aligned} x(k+1) &= f(x(k),\ u(k)) + w(k) \\ y(k) &= hx(k) + v(k) \end{aligned} \quad (8)$$

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:

$$\begin{aligned} \hat{x}(k+1|k) &= F(k)\hat{x}(k|k) + u(k) \\ P(k+1|k) &= F(k)P(k|k)F^T(k) + Q(k) \end{aligned} \quad (9)$$

Measurement update (correct) step:

$$\begin{aligned} K(k+1) &= P(k+1)H^T(k+1) \\ &\quad \times \left[H(k+1)P(k+1|k)H^T(k+1) + R(K+1)\right]^{-1} \\ \hat{x}(k+1|k+1) &= \hat{x}(k+1|k) \\ &\quad + K(k+1)\left[y(k+1) - H(k+1)\hat{x}(k+1|k)\right] \\ P(k+1|K+1) &= \left[I - K(k+1)H(k+1)\right]P(k+1|k) \end{aligned} \quad (10)$$

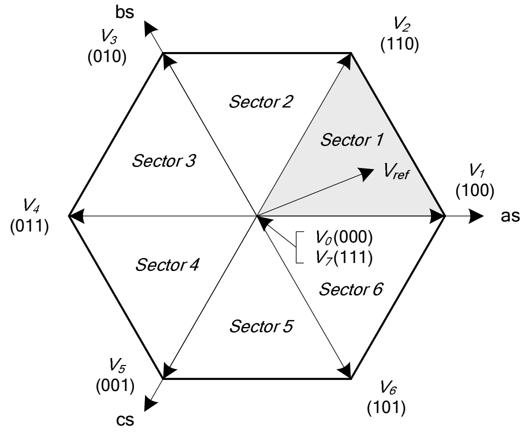

Fig. 2. Space vector modulation.

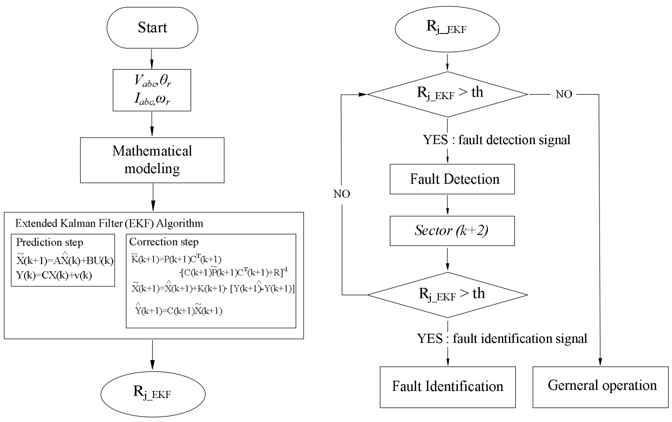

Fig. 3. Flowcharts for fault diagnosis using EKF.

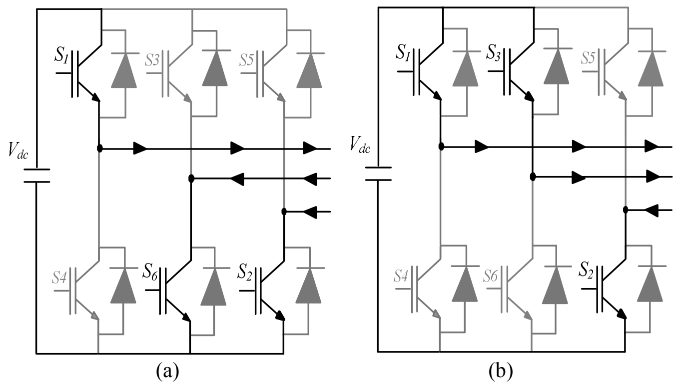

Fig. 4. Effective voltage vector (a) $V_1(100)$ (b) $V_2(110)$.

TABLE I
RESISTANCE VARIATION FOR SECTOR 1-6

	V_1 (100)	V_2 (110)	V_3 (010)	V_4 (011)	V_5 (001)	V_6 (101)
S_1	R_a ↑ R_b ↑ R_c ↑	R_a ↑ R_b ↓ R_c –	•	•	•	R_a ↑ R_b – R_c ↓
S_3	•	R_a ↓ R_b ↑ R_c –	R_a ↑ R_b ↑ R_c ↑	R_a – R_b ↑ R_c ↓	•	•
S_5	•	•	•	R_a – R_b ↓ R_c ↑	R_a ↑ R_b ↑ R_c ↑	R_a ↓ R_b – R_c ↑
S_4	•	•	R_a ↑ R_b – R_c ↓	R_a ↑ R_b ↑ R_c ↑	R_a ↑ R_b ↓ R_c –	•
S_6	R_a – R_b ↑ R_c ↓	•	•	•	R_a ↓ R_b ↑ R_c –	R_a ↑ R_b ↑ R_c ↑
S_2	R_a – R_b ↓ R_c ↑	R_a ↑ R_b ↑ R_c ↑	R_a ↓ R_b – R_c ↑	•	•	•

• no effect – no change

where, P is covariance matrix, K is kalman gain. The $P(k+k|k)$ 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. A quit open subject is the choice of the initial value for the matrices R, Q, P that, in this paper, have been chosen with a trial-and-error procedure to get the best tradeoff between filter stability and convergence time. Such matrices are given as follows

$$Q = \begin{bmatrix} 0.0005 & 0 \\ 0 & 0.0005 \end{bmatrix}, \quad P = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.1 \end{bmatrix} \\ R = \begin{bmatrix} 0.00001 & 0 \\ 0 & 0.00001 \end{bmatrix} \tag{11}$$

It has been stressed that P is by far the less influent choice in the initial tuning procedure of EKF.

B. Analysis of stator resistance characteristics for open-phase fault

As shown in Fig. 2, the operation region of the PMSM drive system is divided into the six triangle domains, denoted from the *Sector 1* to the *Sector 6*, in the space vector pulse width modulation (SVPWM) hexagon. The timing flowchart of the proposed fault detection/identification scheme is illustrated in Fig. 3, where stator resistances of PMSM are estimated by EKF in real time. Once the stator resistances are estimated, they are compared with the given threshold value (th) to determine a fault condition. The proposed simple algorithm for detecting a fault can be derived based on the facts that when the open switch faults occur, each phase resistances exhibit a sudden variation in the different direction, dependant on the PMSM operation in the (SVPWM) hexagon. For example, assuming that the switch, S_1, fails in a open condition and the PMSM operates in the Sector 1 shown in Fig. 2, two effective vectors of the $V_1(100)$ and $V_2(110)$ is generated from inverter output. Consider the switch configurations under the $V_1(100)$ and $V_2(110)$ vectors, illustrated in the Fig. 4. Before open fault of the switch S_1, the $V_1(100)$ is configured that the phase A is connected to the positive bus, and the phase B and phase C are tied to the negative bus. The $V_2(110)$ is configured with the phase A and phase B to the positive bus, and the phase C to the negative bus. After the open fault, however, the $V_1(100)$ has zero currents in each phase, and accordingly, all stator resistances of each phase increase. For the $V_2(110)$, current on the phase A becomes zero, and the phase B and C increase slightly for compensating q-axis current reduced by fault phase as

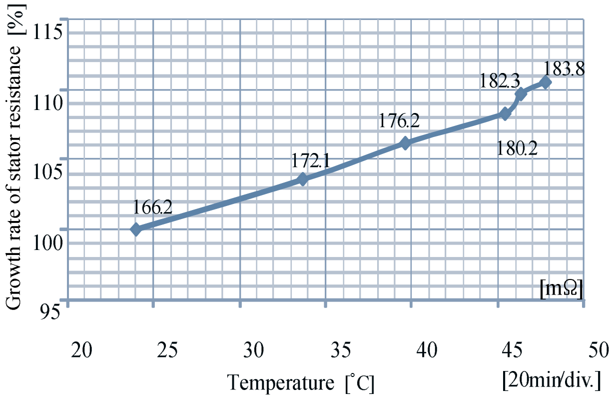

Fig. 5. The growth rate of stator resistance for temperature.

compared to general operation. Consequently, the open fault of the S_1 at the Sector 1 can be detected by observing the variation of stator resistances, such as (i) the stator resistance R_a (of the phase A) continuously increase for both $V_1(100)$ and $V_2(110)$, (ii) the stator resistance R_b (of the phase B) increase for the $V_1(100)$, but decrease for the $V_2(110)$, and (iii) the resistance R_c (of the phase C) increase for the $V_1(100)$, and remain without any variation during the $V_2(110)$. By applying this principle, the variation characteristics of stator resistance to detect open-phase fault is analyzed definitely in *Sector 1-6*.

C. Fault Detection

Generally the stator resistance of PMSM is changed by the variation of temperature. A variation of temperature can cause a significant variation in stator resistance. However, the stator resistance under general operation is determined by the temperature dependence, which is given by

$$R = R_0(1+\alpha\Delta T) \tag{12}$$

where, R_0 is resistance at the reference temperature $T=25$ ℃, α is resistance temperature coefficient, and ΔT is temperature increase. If the open-phase fault occurs, the stator resistance of a faulty phase estimated by EKF is rapidly changed. The stator resistance varied by temperature is distinguished clearly from that open-phase fault by its change rate. Therefore, the threshold value for detecting open-phase fault must be larger than variation of stator resistance for temperature effect. Thus, a 250W PMSM using the laboratory prototype is tested directly in order to measure stator resistance for temperature variation. Fig. 5 shows the growth rate of stator resistance for temperature change. The threshold value is set to the 150% of nominal resistance because the stator resistance may increase by a value up to 20% of its nominal value during general operation. The algorithm for the fault detection is given by

$$\begin{cases} F_D = 1 & \text{if } R_{th} < R_{j\_EKF} \\ F_D = 0 & \text{if } R_{th} > R_{j\_EKF} \end{cases} \quad at \quad Sector\,(k) \tag{13}$$

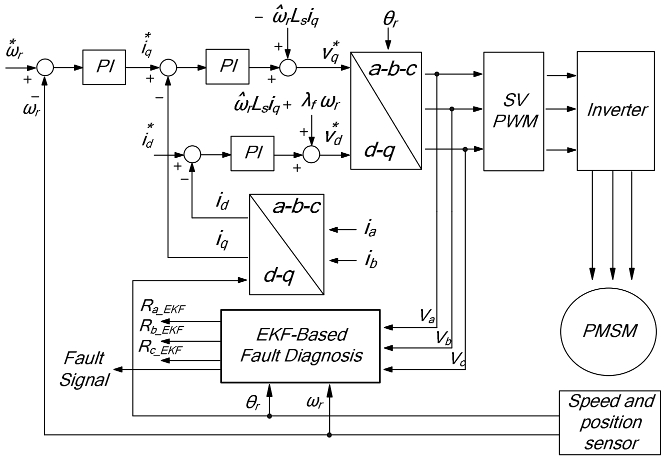

Fig. 6. Block diagram of the proposed EKF-based fault diagnosis.

TABLE II
SPECIFICATION OF PMSM USED IN SIMULATION

Parameters	Symbols	Values
Number of pole pairs	N_p	4 pole
Stator resistance	R	4.3 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

where R_{th} is the threshold value of stator resistance to detect the open-phase fault continuously. If the stator resistance (R_{j_EKF}) estimated by EKF continuously is larger than the threshold value (R_{th}), the fault detection signal (F_D) changes from low to high.

D. Fault Identification

After detection, it is possible to identify the position of faulty phase during a minimum two *Sector*. Similar phenomena are observed in other *Sector* shown in Fig. 2. The identification of open-phase fault is obtained by the fault identification signal (F_I) when the *Sector(k)* is converted to *Sector(k+2)*. The algorithm for the fault identification is given by

$$\begin{cases} F_I = 1 & \text{if } R_{th} < R_{j\_EKF} \\ F_I = 0 & \text{if } R_{th} > R_{j\_EKF} \end{cases} \quad at \quad Sector\,(k+2) \tag{14}$$

The fault diagnosis is achieved by the fault signal (F_D, F_I) at *Sector (k+2)*. Table I shoes how fault diagnosis algorithm under open-phase fault is achieve in *Sector 1-6* and the stator resistance change for the relationship between switching state of Sector1-6 and open-phase fault switches.

The block diagram for overall structure of the proposed fault diagnosis system is shown in Fig. 6.

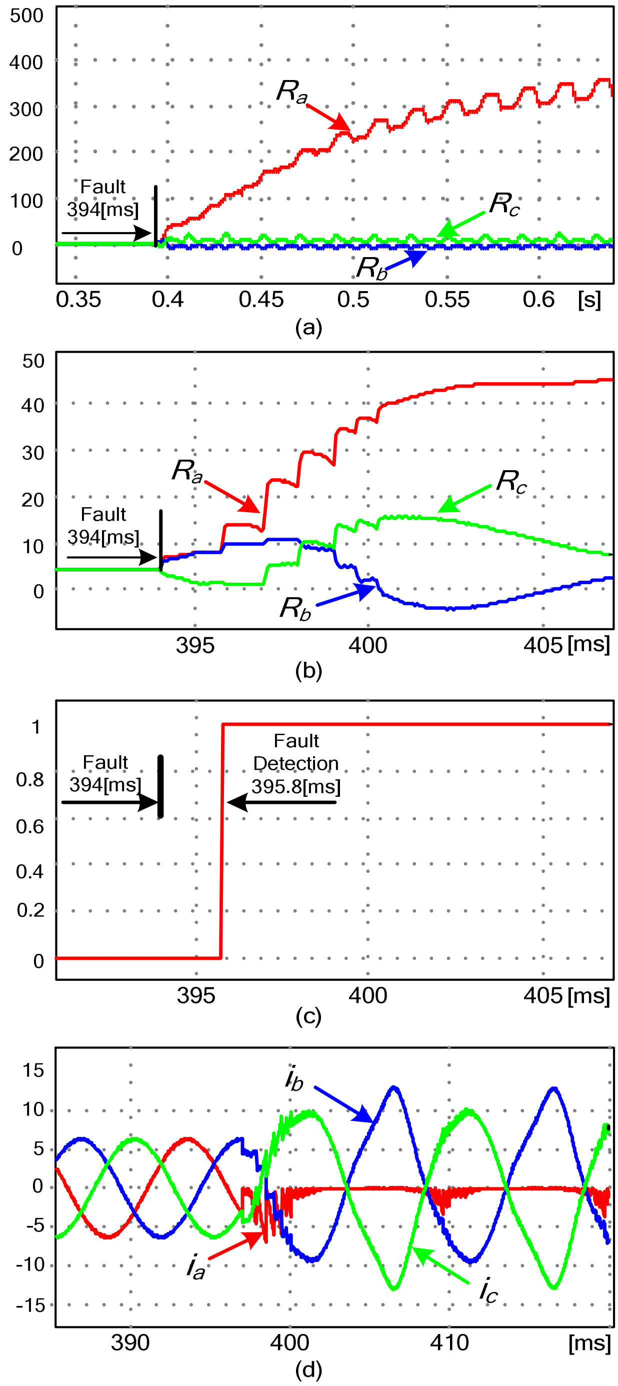

Fig. 7. Simulation results in switch S_1 fault. (a) Estimated stator resistances [Ω]. (b) Extended stator resistances [Ω]. (c) Fault detection signal of phase A. (d) Current waveform [A].

V. SIMULATION

In order to verify a novel fault diagnosis system, a computer simulation was performed along with the existing fault diagnosis system. Simulations are performed by using PSIM simulator to prove the feasibility of the proposed algorithm. The specification of the PMSM is as Table II. Fig. 7(a)-(d) show simulation results of a novel proposed method

Fig. 8. Experimental setup for proposed fault diagnosis.

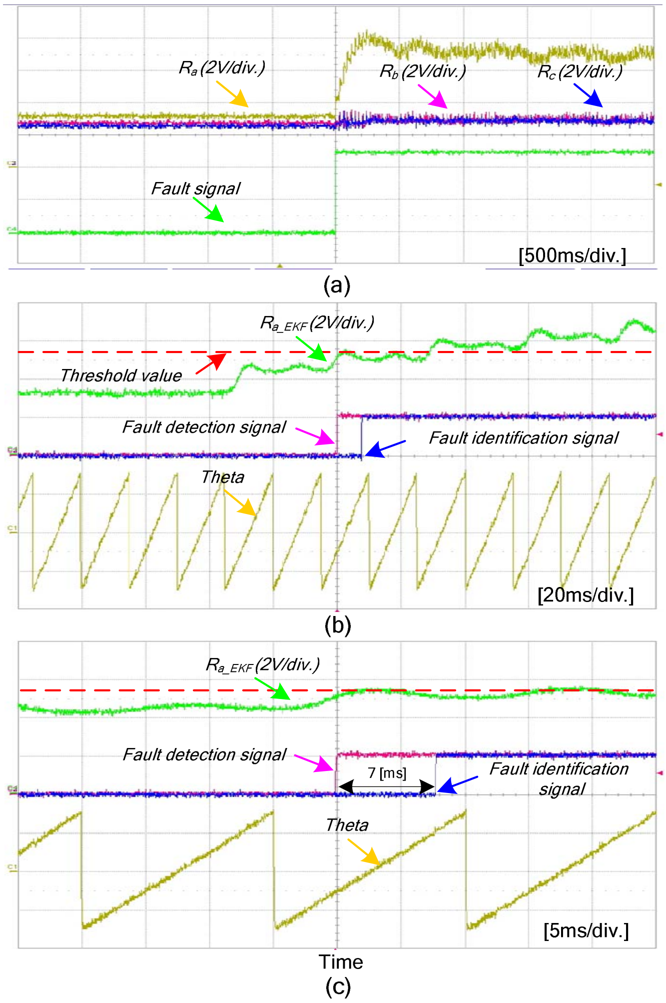

Fig. 9. Experimental results in switch S_1 fault. (a) Estimated stator resistances[Ω] and fault signal. (b) R_{a_EKF}, Fault detection signal, Fault identification signal and Theta. (c) Extended (b) waveforms.

by EKF when the open-phase fault of the switch S_1 happens. The open-phase fault of phase A occurs at 0.394[s] in Sector 1. The EKF algorithm computes a new set of estimated parameters in order to provide the best approximation of stator resistances in the faulty condition. Thus, the fault diagnosis is considered for abnormal variation of the stator resistances estimated by EKF. As shown in Fig. 7(a), estimated stator resistances suddenly increase. After the fault of switch S_1, stator resistances of each phase differently appear. Because of open fault of switch S_1, stator resistance of phase A in comparison with other stator resistance rapidly is changed. Therefore, Fig. 7(c) shows the fault detection signal of phase A at 395.8[ms]. In this profile, the fault detection signal is achieved by applying threshold value that is set to the 150% of nominal stator resistance. Fig. 7(d) shows current waveform. The current of phase A becomes zero within about 11[ms] due to open-phase fault of phase A and the current of phase B and C increase slightly for compensating q-axis current reduced by fault phase as compared to general operation.

VI. Experimental Results

In order to verify the proposed fault diagnosis algorithm, an experiment was performed in the same simulation conditions and designed laboratory prototype is shown in Fig. 9. The main controller was configured by using (DSP) TMS320VC33 and the sampling time in the control algorithm was 50μs. The inverter used in the experiment was implemented with (IPM) PM20CJ060 devices. A 250 W PMSM was coupled with laboratory in order to test proposed fault diagnosis algorithm.

In this work, open-circuit fault of switch (S_1) was described by the enforced off-signal of gate drive at the fault occurrence. Fig. 9(a) shows experimental results for estimated stator resistances R_a, R_b and R_c and fault signal in switch S_1 fault. After fault occurrence, R_a of fault phase suddenly increases. If stator resistance value R_a is larger than the given threshold value (th), the fault detection signal happens and then the fault identification signal occurs within two Sector about 7[ms] as shown in Fig. 9(b) and (c). From the detailed investigation of the simulation and experimental results, the feasibility is fully verified.

VII. Conclusion

This paper proposes the fault diagnosis for open-phase faults of PMSM drives using EKF. The EKF are used to estimate stator resistance of PMSM in real time. Once the stator resistances are estimated, they are compared with the given threshold value (th) to determine a fault condition. The proposed simple algorithm for detecting a fault can be derived based on the facts that when the open switch faults occur, each phase resistances exhibit a suddenly variation in the different direction, dependant on the PMSM operation in the (SVPWM) hexagon. The proposed diagnosis scheme is implemented without any extra devices. Moreover, since it uses a simple algorithm by analyzing only estimated stator resistances of each phase, the detection speed becomes fast. The feasibility of the proposed fault diagnosis scheme is proved by several simulation and experimental results.

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