Open Phase Faults Detection in PMSM Drives Based on Current Signature Analysis

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***Abstract*—This paper deals with monitoring condition of electrical failures in variable speed of permanent magnet synchronous motor (PMSM) drives by stator current signature analysis. The objective of this study is to develop a detection method for the open phase fault in PMSM drives. The main idea consists in minimizing the number of sensors allowing the open stator phase fault of the system to study. The harmonics produced by current spectral analysis fault-related components are studied. The current waveform patterns for various modes of open phase winding are investigated. Simulation and experimental results are presented using a 1.1 kW, 6 poles three-phase PMSM. Comparison of simulation and experimental results show that the method is able to detect the open-phase fault in PMSM drive.**

***Index Terms*—Permanent magnet synchronous motor (PMSM), variable speed controllers system, open stator phase fault, spectrum analysis, fault signatures.**

I. NOMENCLATURE

α-β	Stationary axis reference frame quantities.
d-q	Synchronous axis reference frame quantities.
i_α, i_β	Stator α and β axis currents.
i_d, i_q	Stator d and q axis currents.
v_d, v_q	Stator d and q axis voltages.
Φ_d, Φ_q	Stator d and q axis flux linkages.
L_d, L_q	Stator d and q axis inductances.
Φ_{md}	Permanent magnet flux linkage.
K_e	Back-EMF coefficient constant.
K_t	Torque constant.
R_s	Stator resistance.
J	Total rotor inertia.
B	Viscous friction coefficient.
N_p	Number of the pole pairs.
θ	Electrical rotor position.
ω	Electrical rotation speed.
T_e	Electromagnetic torque.
T_l	Load torque.

II. INTRODUCTION

Nowadays, due to its high efficiency, high ratio of torque to weight, high power factor, faster response and rugged construction, PMSM is the most widely used for high performance variable speed in many industry applications [1]. They have increasingly been used in electrical vehicles, aircraft, nuclear power stations, submarines, robotic applications, medical and industrial servo drives. In some of these applications, continuous operation is necessary and thus a break down of the PMSM drive is unacceptable.

Early detection of abnormalities in the PMSM will help to avoid expensive failures. Indeed, the detection, location, and analysis of faults play a very important role in good operation of the electrical machines and they are essentials for major concerns such as the efficiency and the performance of applications involving PMSM.

Generally, the improvement of the reliability of the PMSM can be obtained by reinforced performance during operation and by implementation security procedures [2]. In recent years, a number of papers have been published to detect inverter faults occurred in PMSM drives [3]–[12]. These faults types can be occurred in stator, rotor PMSM or in the power electronics converter. In [1], [3], [4], the authors have studied stator faults and single-phase for open circuit faults. The short-circuit faults have been investigated in [6]–[8], using a fault tolerant controller. The rotor faults have been demonstrated in [9]. Open-circuit faults and IGBT gate signals are turned off in voltage source inverter as shown in [9], [10].

This paper presents a study of the occurrence of open phase faults detection in PMSM drives. The method used for detection of open phase faults is based on harmonics of the stator current or by the current signature analysis.

Contributions of this paper include several aspects: First, a dynamic state space model of PMSM is proposed. Second, the simulated results of healthy and faulty three-phase PMSM drives are presented. Finally, we will present the simulation and experimental results for healthy and open phase faults of PMSM drives.

III. PMSM MODEL FOR FAULT DETECTION

Let we develop the state space model of the PMSM in a synchronous reference frame. Fig. 1 shows a general purpose of three-phase inverter fed PMSM drive.

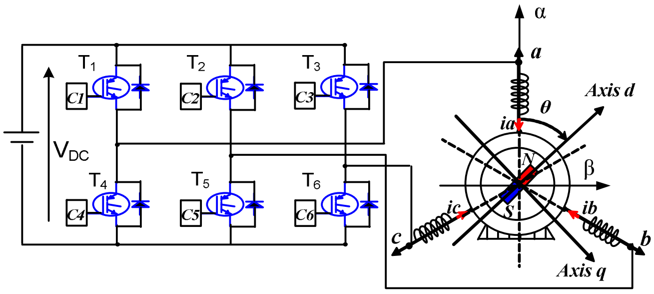

Fig. 1. PWM voltage source inverter fed PMSM.

The stator d and q axis flux linkages can be expressed as:

$$\Phi_d = L_d i_d + \Phi_{md} \tag{1}$$

$$\Phi_q = L_q i_q \tag{2}$$

The stator d and q axis voltages can be described by the following equations:

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$$\begin{aligned} v_d &= R_s i_d + L_d(\frac{d}{dt}i_d) - \omega L_q i_q \\ v_q &= R_s i_q + L_q(\frac{d}{dt}i_q) + \omega(L_d i_d + \Phi_{md}) \end{aligned} \tag{3}$$

The electromagnetic torque is given by the following equation:

$$T_e = N_p(\Phi_{md} i_q + (L_d - L_q) i_d i_q) \tag{4}$$

By using Eqs. (3) and (4) the state space model of the PMSMS expressed in the *d-q* synchronous reference frame is described by:

$$\begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \\ \frac{d\omega}{dt} \\ \frac{d\theta}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{\tau_d} & \frac{L_q}{L_d}\omega & 0 & 0 \\ -\frac{L_d}{L_q}\omega & -\frac{1}{\tau_q} & -\frac{\Phi_{md}}{L_q} & 0 \\ N_p{}^2\frac{L_d - L_q}{J}i_q & N_p\frac{K_t}{J} & \frac{-B}{J} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ \omega \\ \theta \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} & 0 & 0 \\ 0 & \frac{1}{L_q} & 0 \\ 0 & 0 & -\frac{N_p}{J} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_d \\ v_q \\ T_l \end{bmatrix} \tag{5}$$

where $\tau_d = \frac{L_d}{R_s}$ the d-axis time constant and $\tau_q = \frac{L_q}{R_s}$ the q-axis time constant.

The mathematical representation of the PMSM will be used for simulation of stator open phase faults.

IV. SIMULATION OF FAULTY PMSM DRIVE

This section presents simulation results obtained of faulty PMSM drive for the proposed open phase fault detection.

We simulate a simplified *d-q* axis electrical model of a three-phase PMSM drives using Matlab-Simulink. The simulation demonstrates a typical start-up of the motor with open phase fault. The reference rotor speed is set at 1500 rpm with a step load torque $T_l = 2$ Nm applied to the system at t = 0.1 s, as it is shown in Fig. 2. The instantaneous torque for the faulty PMSM drive can be seen in Fig. 3. This fault may also produce a small torque ripples.

During the acceleration, the maximum q-axis stator current reaches to 8 A. Except for the transition during the first, the d-axis controlled keeps the d-axis current at zero. When t = 0.1 s, a load torque is applied and we can observe that the q-axis stator current is directly proportional to the electromagnetic torque, while the d-axis current oscillate within 1.2 A and -1.2 A with an average value equal to zero as shown in Fig. 4.

The open-phase fault produces electromagnetic torque oscillations which cause abnormal rotor vibrations and give abnormalities in the drive's operation. The d-q axis stator fluxes are affected with ripples as shown in Fig. 5.

Details of the phase current are shown in Fig. 6 for the healthy and faulty motor stator current at 50% torque load. After the transient mode, the phase currents reach the steady state mode with a maximum value of 2.1 A (Fig. 6 (a)).

The three phase currents are shifted $\frac{2\pi}{3}$, thus, we find well of balanced operation in PMSM. Fig .6 (b) shows the simulated phase currents i_a and i_b in the presence of an open phase fault in PMSM. We can note that the amplitude of these components increases by approximately 60 %, and the two phases currents are shifted 2π, thus the risk of destruction of stator winding.

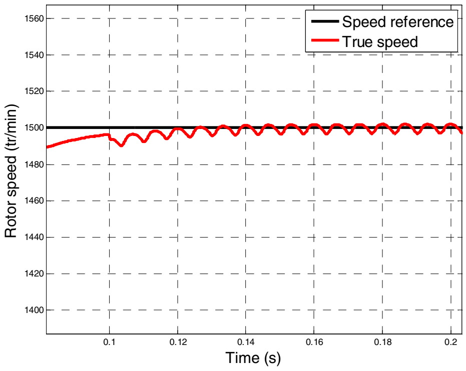

Fig. 2. Zoom of simulation speed response during the open stator phase.

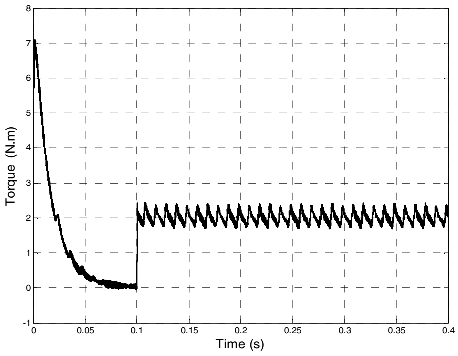

Fig. 3. The electromagnetic torque during the open stator phase.

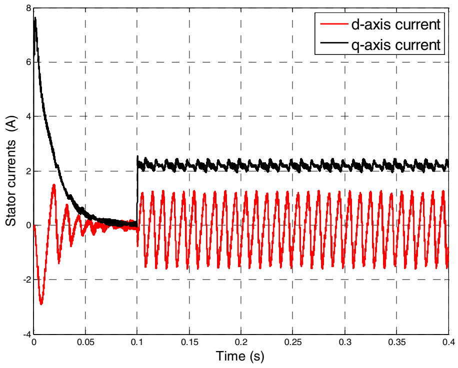

Fig. 4. Transformed d-q currents during the open stator phase.

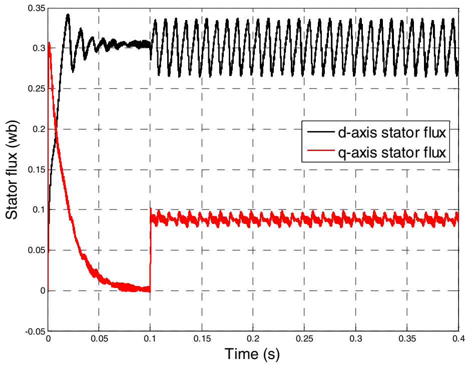

Fig. 5. Transformed d-q flux during the open stator phase.

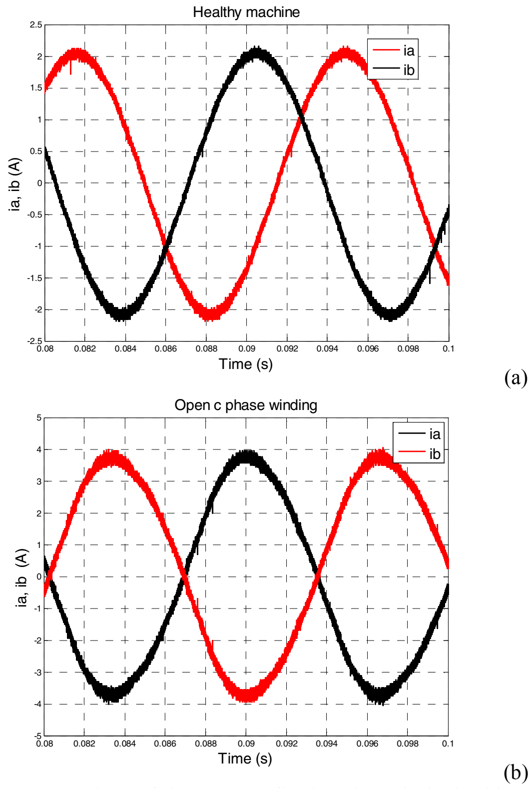

Fig. 6. Comparison of the currents flowing through the healthy motor (a) and the open stator phase (b).

Based on these results, a generation of frequency components and their amplitudes can be used to a suitable signature for the detection of the open phase fault.

The parameters of PMSM are SMV 115 UM 30 from Leroy-Sommer and listed in Table I.

V. EXPERIMENTAL RESULTS

During the use of the experimental system described by the Fig. 7, we have observed that if the open phase fault occurs in the electrical drives, the PMSM continues under degraded operation mode. So, an open phase fault involves making possible the operation in tolerant fault control of PMSM drive [11], [12]. This operation mode is not desirable and can cause a destruction of the stator phase winding. Therefore, we are interested in this default type for the determination of signatures to allow the detection and the localization of the open phase fault.

The following section presents experimental results to demonstrate the previously derived signatures analysis used for PMSM fault. The PMSM under test is a 400 V, 1.1 kW, three phase permanent magnet synchronous motor with 3.2 Nm nominal torque. It is coupled to a magnetic power break used as a load torque and the UMV 4301 vector controls speed drives. The dSpace system used is a DS1103 with a Motorola Power PC604e with 400 MHz CPU clock. The system is mounted (Fig. 7) making the connection easy between the board to different devices, the host computer of the dSpace software and Matlab-Simulink environment.

The test-bed has a position encoder used for real speed measurement. A high sampling frequency is chosen to include several inverter switching frequency harmonics at 3 kHz. The line current is measured by Hall LEM LA 55-NP and it is converted through a 16 bits A/D converter. The stator current components i_α and i_β in the stator axis frame are obtained through Clark transformations.

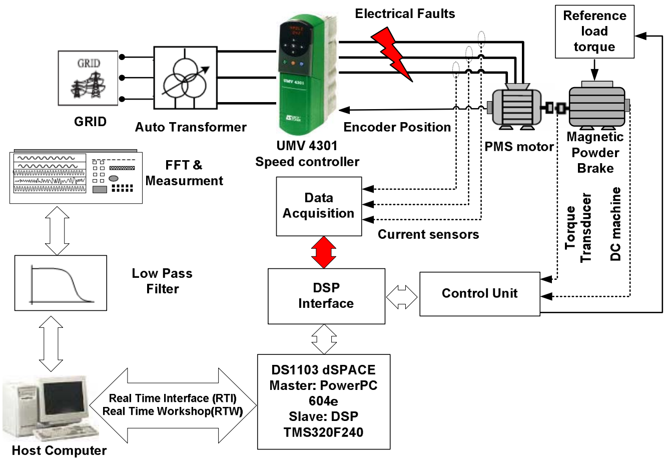

Fig. 7. Configuration of the experimental system.

A. Harmonic analysis of PMSM current

Fig. 7 illustrates the experimental setup. The PMSM is supplied by the speed controller equipped with the Rotor Field Oriented Control (RFOC) strategy. This system is operating in speed control closed loop condition. Fig. 8, present the experimental results according to the electromagnetic torque of healthy and faulty machine. The open phase fault of phase c occurs at t = 7 sec. Figs. 9 (a) and (b) show the experimental results for the phase currents i_a and i_b in the healthy and faulty operation mode, respectively. The open phase fault of the PMSM introduced an unbalance in the stator winding currents.

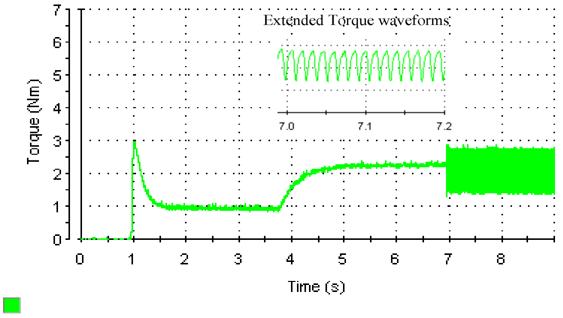

Fig. 8. Experimental results of the electromagnetic torque under an open stator phase.

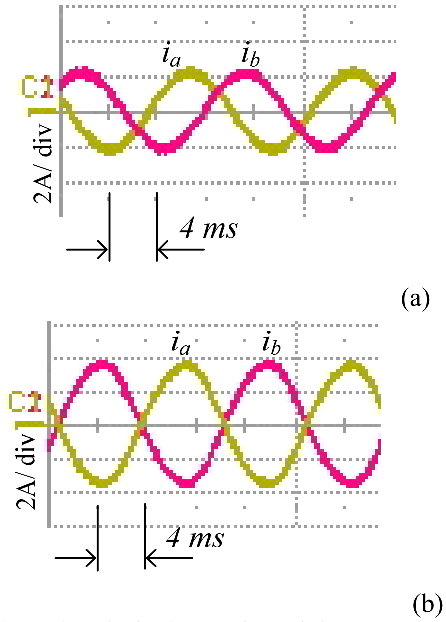

Fig. 9. Experimental results for the waveform of phases currents, (a) healthy operation mode, (b) open phase fault.

This fault causes strong oscillations in the electromagnetic torque. The currents of the phase currents are modulated in amplitude and frequency. For this reason, the current spectrum can be used to detect the open phase fault. The spectrum is obtained using a Fast Fourier Transform (FFT) that is performed on the stator current. Figs. 10 (a) and (b) show the comparative stator current spectrum analysis of a loaded 6-pole PMSM, in healthy and faulty machine with an open phase fault. The current characteristics values frequency of 2· *f*s, 3· *f*s, 4· *f*s and 5·*f*s are shown in the Figs. 10. (a) and (b).

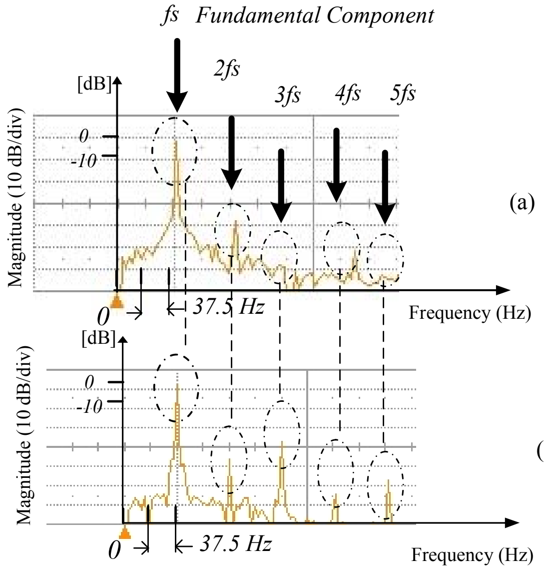

Fig. 10. Frequency spectrum of the stator current for the following operating conditions, a) healthy motor, b) open stator phase.

The current spectrum can highlight the change in the spectra for the type of the open phase fault. The magnitude peak at 75 Hz corresponds to a fundamental component due to the rotor speed operation. It can be concluded that the evolution of the spectra peaks at 150, 225, 300, 375 and 450 Hz has shown that there is an open phase fault in PMSM. In addition, Fig. 10 makes clear that the difference between balanced operation and under open phase fault cases follows the spectra peaks of a phase stator currents. The amplitude of these components increases by approximately 10 dB where a new faulty phase exists as well. It is to be announced that the frequency components are the same for different open phase fault cases. Therefore, it is not possible to locate the faulty phase with the spectrum current analysis technique. For that, we develop the current fault signature technique.

B. *Current fault signatures*

The detection of these faults can be implemented by using the phase angle or checking the trajectory of the vector in α–β axis because the phase plane plot for each open phase is unique [13]. Fig. 11 shows the trajectories for healthy conditions which are plotted for the stator current. This is confirmed by Fig. 9 (a), in which the locus of the phase current vectors is drawn in the plane, one can recognize a circle centered on center with a radius of 2.5 A.

In Figs. 12, 13 and 14, the trajectories for different open phase are plotted. Fig. 11 shows the phase plane plot of the stationary reference frame α and β axis components of the stator currents for the open a phase case. It is observed in the trajectories that one can recognize a right-hand. Figs. 13 and 14 show the phase plane plot of the stationary reference frame α and β axis components of the stator currents for the open b and c phases. It is observed in the trajectories that one can recognize a left-hand and right-hand respectively.

- Healthy stator phase

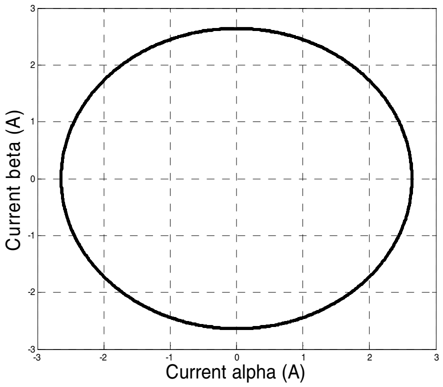

Fig. 11. Locus of the α-β currents during the healthy PMSM.

- Opening of the a phase stator winding

$$i_a = 0 \text{ and } \begin{cases} i_\alpha = 0 \\ i_\beta = \sqrt{2} i_b \end{cases} \tag{6}$$

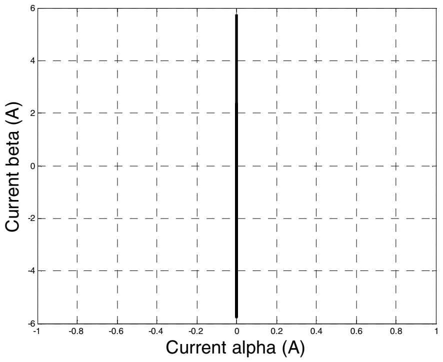

Fig. 12. Locus of the α-β currents for open a phase winding.

- Opening of the b phase stator winding

$$i_b = 0 \text{ and } \begin{cases} i_\alpha = \sqrt{\frac{3}{2}} i_a \\ i_\beta = i_\alpha \end{cases} \tag{7}$$

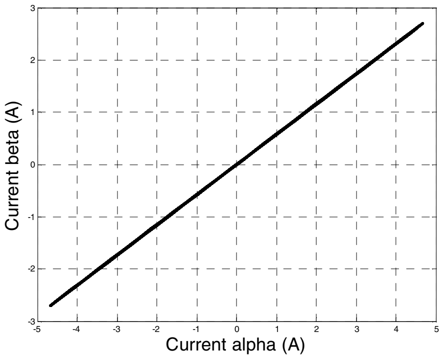

Fig. 13. Locus of the α-β currents for open b phase winding.

- Opening of the c phase stator winding

$$i_c = 0 \text{ and } \begin{cases} i_\alpha = \sqrt{\dfrac{3}{2}}\, i_a \\ i_\beta = -i_\alpha \end{cases} \qquad (8)$$

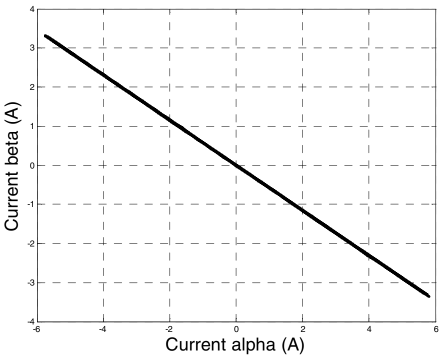

Fig. 14. Locus of the α-β currents for open c phase winding.

The different simulation and experimental results are presented to show the performance of the proposed method. The advantage of this method is well identified as a standard today since it is very simple, it needs only one current sensor by machine and it is based on the stator currents signal. The experimental results are compared with the simulation results to illustrate the good agreement that exists between the simulation model and the real system.

A schematic representation of the experimental setup used for signature analysis is displayed in Fig. 15.

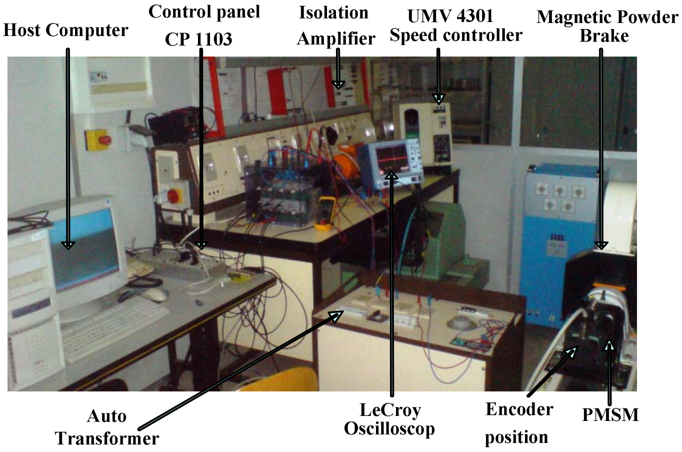

Fig. 15. Photo of the experimental setup.

VI. CONCLUSION

This paper has proposed a method allowing the detection of the open phase fault in PMSMS drives based on current harmonic signature. For this diagnosis, we developed the state space model of the PMSMS expressed in the d-q synchronous reference to study the phenomena occurred in the stator current. The spectrum analysis of this current allowed detection of the open phase fault occurred thanks to the spectrum current analysis. Moreover, it is not possible to detect the cases of opening phase as abnormal conditions basis only on spectrum current analysis. For this reason, we have to use the fault signatures provided by the stator current. Experimental validations are given for the open phase stator winding. The simulation and experimental results approve the effectiveness of the methods for the open phase fault detection in PMSM drive. A good procedure of a method detection for the open phase to affect the elements in the association plots. The proposed method permits a quick detection and localization of the open phase fault while only supervising stator-currents. The fault detection is obtained without needing any additional materials and uncomplicated calculations.

VII. APPENDIX

TABLE I
PERMANENT MAGNET SYNCHRONOUS MOTOR PARAMETERS

Parameters		Specification	
R_s	6.2 Ω	Rated power	1.1 kW
L_d	25.025 mH	Rated voltage	400 V
L_q	40.17 mH	Rated current	2.53 A
Φ_{md}	0.305 Wb	Number of pole pairs	3
K_e	0.535 V.s.rad^{-1}	Rated speed	3000 r/min
K_t	0.9149 Nm/A	Rated torque	4.1 N.m
J	0.0036 Kg.m^2	B	0.0011 Nm.s.rad^{-1}

VIII. ACKNOWLEDGMENT

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