

A Real-Time Open Phase Faults Detection for IPMSM Drives Based on Discrete Fourier Transform Phase Analysis

A. Khlaief⁽¹⁾⁽²⁾, M. Boussak⁽¹⁾, *Senior Member, IEEE*, A. Châari⁽²⁾

⁽¹⁾ Laboratoire des Sciences de l'Information et des Systèmes (LSIS) UMR CNRS 7296 – Ecole Centrale Marseille (ECM)
Technopole de Château Gombert – 13451 Marseille Cedex 20 – France–mohamed.boussak@centrale-marseille.fr

⁽²⁾ Unité de recherche en Commande, Surveillance et Sûreté de fonctionnement des Systèmes (C3S)
Ecole Supérieure des Sciences et Techniques de Tunis (ESSTT)
5 Avenue Taha Hussein – BP 56, Bab Manara – 1008 Tunis
amor.khlaief@centrale-marseille.fr, abdelkader.chaari@yahoo.fr

Abstract—Permanent Magnet Synchronous Motors (PMSM) are many used to high performance applications. Accurate faults detection can significantly improve system availability and reliability. This paper investigates the experimental implementation and detection of open phase faults in interior permanent magnet synchronous motor (IPMSM). The proposed method of open phase fault detection is based only on stator current measurement. The objective of this paper is to develop a new detection method for the open phase fault in IPMSM drives. The main idea consists in minimizing the number of sensors allowing the open stator phase fault of the system to study. This paper proposes the fault diagnosis for open-phase faults of IPMSM drives using a Discrete Fourier Transform phase. The current waveform patterns for various modes of open phase winding are investigated. Discrete Fourier Transform is used for the phases ($\varphi_\alpha, \varphi_\beta$) calculation. Experimental results show that the method is able to detect the open-phase faults in IPMSM drive. The experimental implementation is carried out on powerful dSpace DS1103 controller board based on the digital signal processor (DSP) TMS320F240. Experimental results obtained confirm the aforementioned study.

Keywords—Permanent magnet synchronous motor (PMSM), open stator phase fault, Discrete Fourier Transform (DFT) phase, digital signal processor (DSP).

I. NOMENCLATURE

$d - q$	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
K_e	Back-EMF coefficient constant
$\hat{\Phi}_m$	Peak permanent magnet flux
R_s	Stator resistance
J	Total rotor inertia
B	Viscous friction coefficient
N_p	Number of the pole pairs
ω_r, θ	Electrical speed and rotor position
Ω_r	Mechanical rotor speed
T_e, T_l	Electromagnetic torque and load torque
p	Laplace variable
$*$	Reference value
K_{i_Ω} and K_{p_Ω}	Integral and proportional (IP) speed

	controller
$K_{i_{id}}$ and $K_{p_{id}}$	Integral and proportional (PI) d -axis current controller
$K_{i_{iq}}$ and $K_{p_{iq}}$	Integral and proportional (PI) q -axis current controller
$K_{\omega, i_{est}}$ and $K_{\omega, p_{est}}$	Integral and proportional (PI) speed observer controller

II. INTRODUCTION

Recently, permanent magnet synchronous motor (PMSM) are most widely used for high performance variable speed in many industry applications, due to its high efficiency, high ratio of torque to weight, high power factor, faster response and rugged construction. They have increasingly been used in electrical vehicles, aircraft, nuclear power stations, submarines, robotic applications, medical and industrial servo drives.

In some of the industry applications, continuous operation is necessary and thus a breakdown 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 drives 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 phase of the stator current or by the current signature analysis. The phase angle of α - β axis stator currents are measured by the Discrete Fourier Transform (DFT) in real time. If an open-

phase fault occurs, the phase angle of α - β axis stator currents of a faulty phase measured by the DFT is rapidly changed. This characteristic of the phase angle of α - β axis stator currents offer a simple algorithm to detect open-phase fault. Contributions of this paper include several aspects: First, a dynamic state space model of PMSM is proposed. Second, the proposed open phase faults detection and discrete Fourier transform phase analysis are presented. Finally, we will present the experimental results for healthy and open phase faults of PMSM drives.

I. PMSM DRIVES SYSTEM

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.

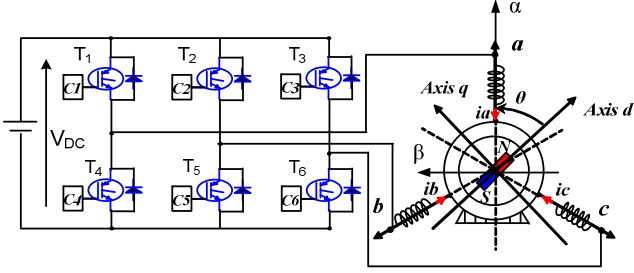


Fig. 1. Voltage source inverter-IPMSM drive.

The permanent magnetization is here modeled by the flux linkage of the magnets with the stator winding Φ_{md} , R_s stator resistance, L_d and L_q are the inductances in d and q directions respectively including leakage and magnetizing components. Besides ω_r is the electrical angular frequency.

$$\frac{d}{dt}\theta = \omega_r \quad (1)$$

The machine voltages in the d - q system are:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_s + \frac{d}{dt}L_d & -\omega_r L_q \\ \omega_r L_d & R_s + \frac{d}{dt}L_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \Phi_{md} \omega_r \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (2)$$

Where N_p is the number of pole pairs, the electromagnetic torque developed by the motor can then be expressed as:

$$T_e = N_p (K_e i_q + (L_d - L_q) i_d i_q) \quad (3)$$

The VFOC of PMSM allows separate closed loop decoupling control of both flux and torque. It is apparent that if we can control d -axis current to be zero, then the torque is directly proportional to q -axis current. Therefore from equation (9) it can be seen that the torque is dependant and can be controlled by the q -axis current only given as follows:

$$T_e = K_t i_q \quad (4)$$

Finally, we can see that the decoupling technique transforms the nonlinear motor model to a linear one which can be controlled by the PI current loop controllers.

The SVM consists, to approach two voltages instantaneous, by control signals of the switches. The main advantage of this technique is that the switching losses are low; the harmonic performance is improved and produces an

improved output voltage for the same dc bus voltage, when compared to a sinusoidal PWM (SPWM).

II. PROPOSED OPEN PHASE FAULTS DETECTION

An open phase fault occurs if a phase is interrupted by some failure. In this case, 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.

A. Discrete Fourier Transform phase analysis

The proposed methodology used for open phase faults detection and localization is based on the phase angle of stator current's Concordia component (i_α , i_β). The signatures used for fault detection and diagnosis are usually the stator three-phase current. These currents are measured by the current sensors. Concordia transformation is used to transform the stator three-phase current i_a , i_b and i_c into α - β axis.

With the system shown in Fig. 1, at first the a-phase stator winding is open, and the α - β axis stator currents is synthesized by a SVPWM inverter as follows:

$$\begin{aligned} i_\alpha &= I_m \sin(\omega_r t + \varphi_\alpha) \\ i_\beta &= I_m \cos(\omega_r t + \varphi_\beta) \end{aligned} \quad (5)$$

where φ_α and φ_β phase angle of α - β axis stator currents

The discrete Fourier transform (DFT) is given by

$$i_{\alpha k} = \sum_{n=0}^{N-1} i_{\alpha n} e^{j \frac{2\pi}{N} kn}, \quad k = 0, \dots, N-1 \quad (6)$$

A simple description of these equations is that the complex numbers X_k represent the amplitude and phase of the different sinusoidal components of the input signal x_n . The DFT computes the X_k from the x_n , while the IDFT shows how to compute the x_n as a sum of sinusoidal components $i_{\alpha n} = \left(\frac{1}{N}\right) X_k e^{j \frac{2\pi}{N} kn}$ with frequency k / N cycles per sample,

where k are the present samples.

$$\text{Re } X[k] = \sum_{n=0}^{N-1} x[n] \cos\left(\frac{2\pi kn}{N}\right) \quad (7)$$

$$\text{Im } X[k] = -\sum_{n=0}^{N-1} x[n] \sin\left(\frac{2\pi kn}{N}\right) \quad (8)$$

In the same way, by writing X_k in polar form, we obtain the sinusoid amplitude A_k / N and phase φ_k from the complex modulus and argument of X_k , respectively:

$$i_\alpha[k] = \sum_{n=0}^{N-1} (\text{Re } i_\alpha[n] + j \text{Im } i_\alpha[n]) e^{-j \frac{2\pi}{N} kn} = \text{Re } i_\alpha[k] + j \text{Im } i_\alpha[k] \quad n = 0, \dots, N-1 \quad (9)$$

$$i_\beta[k] = \sum_{n=0}^{N-1} (\text{Re } i_\beta[n] + j \text{Im } i_\beta[n]) e^{-j \frac{2\pi}{N} kn} = \text{Re } i_\beta[k] + j \text{Im } i_\beta[k] \quad n = 0, \dots, N-1 \quad (10)$$

$$\varphi_{\beta} = Arg(X_{\beta k}) = a \tan 2(\text{Im}(X_{\beta k}), \text{Re}(X_{\beta k})) \quad (12)$$

B. System and fault description

The proposed vector field oriented control of IPMSM drive and open phase faults detection is shown in Fig. 2.

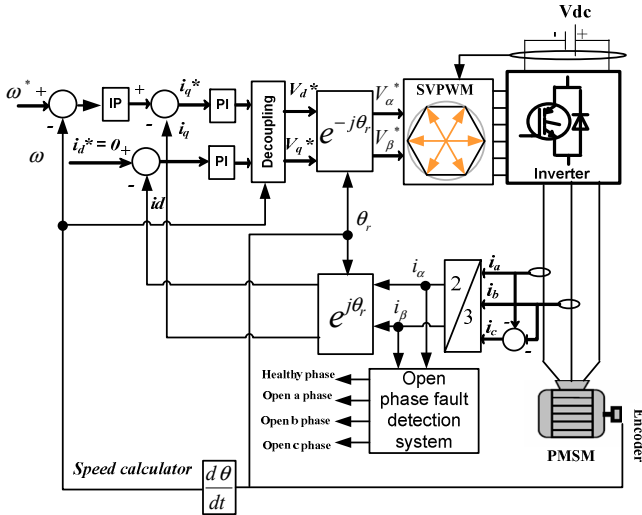


Fig. 2. Flow diagram of PMSM drive and open phase faults detection.

The topology of the examined inverter is given in Fig.1, with a fault in switch 1 indicated by an open gate connection. In case of an open circuit fault, the line currents behave characteristically. Since the faulty transistor cannot conduct any current, the line current can only be positive or negative, depending on which transistor is damaged.

According to the obtained experimental results we note that the stator current's Concordia components phases φ_α and φ_β change when an open phase fault appears. We tested all possible open phase faults and we concluded that variations in phase φ_α and φ_β differ from case to case. We have tested several times and we have noticed that $\Delta\varphi_\alpha = \varphi_{\alpha\text{fail}} - \varphi_{\alpha\text{safe}}$ and $\Delta\varphi_\beta = \varphi_{\beta\text{fail}} - \varphi_{\beta\text{safe}}$ are independent of the initial phase and load variations. The results for all possible cases of open phase faults are summarized in Table I.

TABLE I
RANGE OF PHASES $\Delta\varphi_\beta$, $\Delta\varphi_\alpha$ IN OPEN PHASE FAULTS

<i>Open phase faults</i>	$\Delta\varphi_{\alpha} = \varphi_{\alpha-fail} - \varphi_{\alpha-safe}$	$\Delta\varphi_{\alpha} = \varphi_{\alpha-fail} - \varphi_{\alpha-safe}$
<i>Open a phase winding</i>	$-52 \pm 2^{\circ}$	$-13 \pm 2^{\circ}$
<i>Open b phase winding</i>	$-11 \pm 2^{\circ}$	$75 \pm 2^{\circ}$
<i>Open c phase winding</i>	$18 \pm 2^{\circ}$	$63 \pm 2^{\circ}$

Fault diagnosis based on the Discrete Fourier Transform includes the following steps: Concordia transform, the discrete Fourier transform, and real binary conversion as shown in Fig.3.

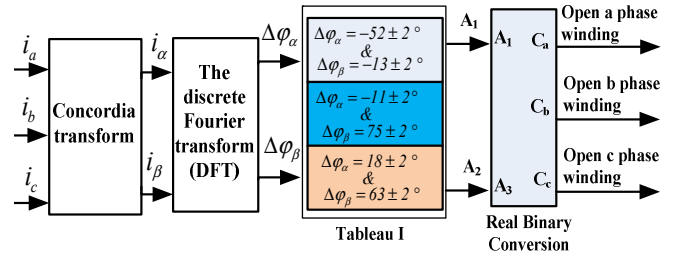


Fig. 3. Processes for early fault detection.

Another, in the process for detecting a fault within phase winding we created two binary variables A_1 and A_2 whose boolean combinations are representative of the various range of phases $\Delta\varphi_\beta, \Delta\varphi_\alpha$. Table II, presents the diagnosis output signals for open phase faults. Table III, illustrates the binary variables A_1 and A_2 according to the faulty phases.

TABLE II
RANGE OF PHASES $\Delta\varphi_\beta, \Delta\varphi_\alpha$ VALUE ACCORDING TO THE BINARY
VARIABLES

Range of phases $\Delta\varphi_\beta, \Delta\varphi_\alpha$	A_1	A_2
$\Delta\varphi_\alpha = -52 \pm 2^\circ$ and $\Delta\varphi_\beta = -13 \pm 2^\circ$	0	1
$\Delta\varphi_\alpha = -11 \pm 2^\circ$ and $\Delta\varphi_\beta = 75 \pm 2^\circ$	1	0
$\Delta\varphi_\alpha = 18 \pm 2^\circ$ and $\Delta\varphi_\beta = 63 \pm 2^\circ$	1	1

TABLE III
REAL BINARY CONVERSION

A_1	A_2	Faults
0	1	C_a (Open a phase winding)
1	0	C_b (Open b phase winding)
1	1	C_c (Open c phase winding)

III. EXPERIMENTAL RESULTS

C. Experimental Setup

A schematic representation of the experimental setup used for discrete Fourier transform phase is displayed in Fig. 15. These algorithms are characterized by repetitive mathematical computation at high-speed, similar to this application where the mathematically intensive field oriented control and space vector modulation algorithms must be run within every 150 μ s sampling period (T_s). A schematic representation of the experimental setup used for open phase fault detection is displayed in Fig. 5. To verify the proposed open phase faults detection in PMSM, a simulation program and the laboratory setup with 1.1-kW permanent magnet synchronous motor (SMV UM 115 from Leroy-Sommer). This characteristics are listed in Table IV, is used with a 4096-pulse incremental encoder, and the magnetic powder brake used as load torque, a commercial 20 KVA three phase inverter based on insulated-gate bipolar transistor (IGBT from SEMIKRON) is supplied by DC bus voltage which provides 540 V with current limitation of about 30A, with dSpace DS1103 laboratory control board was constructed (Fig.4). The DS1103 PPC is a very flexible and powerful system featuring both high computational capability and comprehensive I/O periphery. Additionally, it

features a software interface that allows all applications to be developed in the Matlab/Simulink environment. The system is based on Motorola Power PC604, the DSP subsystem, based on the Texas Instruments TMS320F240 DSP fixed-point processor, the DSP provides 3-phase SVPWM generation making the subsystem useful for drive applications. Two LEM current sensors (LEM LA 100P) are used.

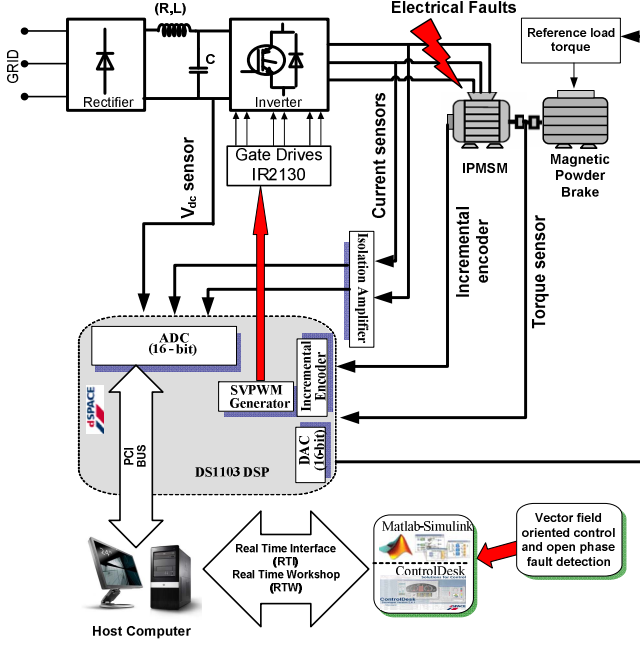


Fig. 4. Experimental system configuration.

A schematic representation of the experimental setup used for signature analysis is displayed in Fig. 5.

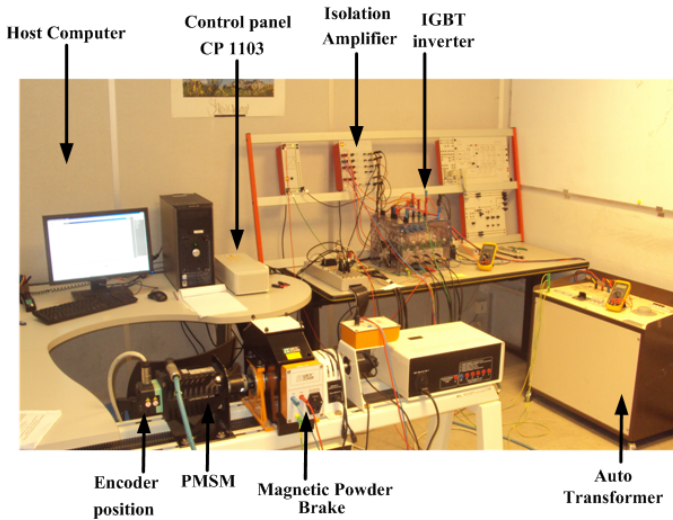


Fig. 5. Photo of the experimental setup.

D. Detection Faults

This section presents experimental results obtained of faulty PMSM drive for the proposed open phase fault detection. Fig. 1 presents the experimental results according to open a phase winding fault condition. This figure shows a typical start-up of the motor without fault, the open phase fault of phase a occurs at $t = 4.5$ s. The reference rotor speed

is set at 500 rpm with a step load torque $T_l = 1.5$ Nm applied to the system at time $t = 1.6$ s, as it is shown in Fig. 2. The instantaneous torque for the faulty PMSM drive can be seen in Fig. 7. This fault may also produce a small torque ripples. During the acceleration, the maximum q-axis stator current reaches to 2 A. Except for the transition during the first, the d-axis controlled keeps the d-axis current at zero. When $t = 4.6$ 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. 8. The open-phase fault produces electromagnetic torque oscillations which cause abnormal rotor vibrations and give abnormalities in the drive's operation. Fig. 9 shows the experimental phase currents i_a , i_b and i_c in the presence of an open phase fault in PMSM. The current Concordia components phases ϕ_α and ϕ_β when open a phase winding as shown in Fig. 10. According to the obtained experimental results we note that the stator current's Concordia components phases ϕ_α and ϕ_β change when an open phase fault appears.

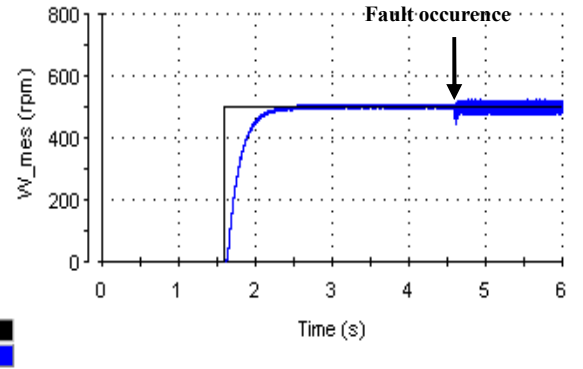


Fig. 6. Reference and measured speed.

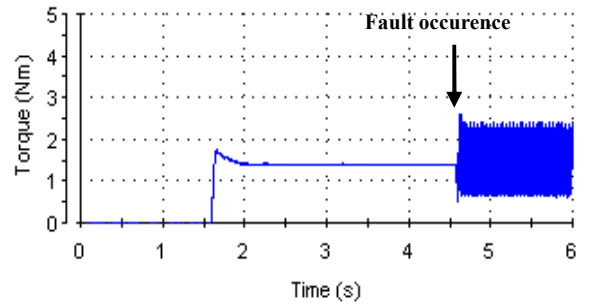


Fig. 7. Experimental results of the electromagnetic torque under an open stator phase.

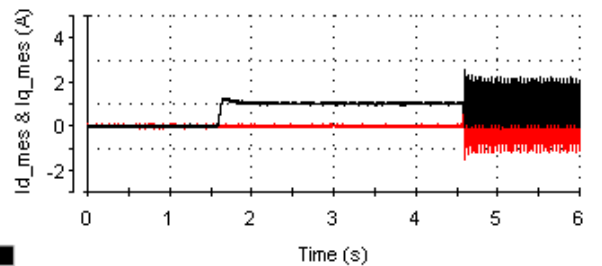


Fig. 8. Transformed d-q currents during the open stator phase.

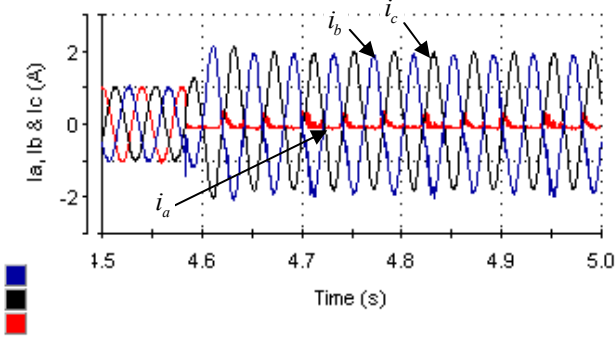


Fig. 9. Measured phase currents during open a phase winding.

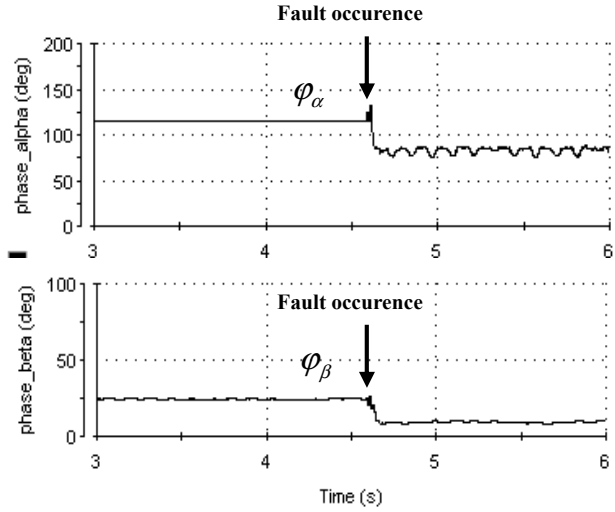


Fig. 10. The current Concordia components phases φ_α and φ_β when open a phase winding.

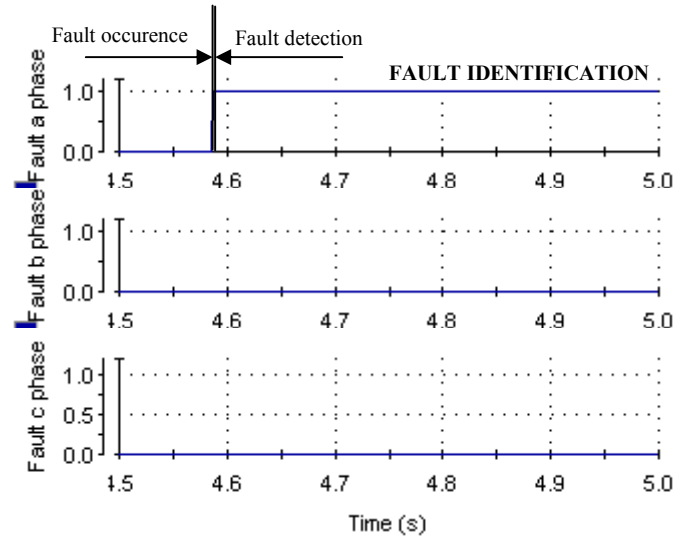


Fig. 11. Faults detection signals of stator phases.

Boolean outputs of open phase detector in open phase fault (phase 1 open phase fault) are presented respectively in Fig. 11. By using the stator current's Concordia components phases φ_α and φ_β , the detection time is less than 10 ms.

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 [12]. Fig. 11 shows the trajectories for healthy conditions which are plotted for the stator current. This is confirmed by Fig. 12, 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. Fig. 12 shows the phase plane plot of the stationary reference frame α and β axis components of the stator currents for the open b phase case. It is observed in the trajectories that one can recognize a right-hand. It is observed in the trajectories that one can recognize a left-hand and right-hand respectively.

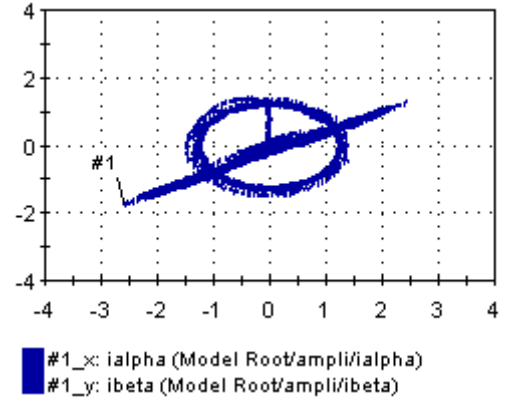


Fig. 12. The current vector trajectory in complex plan α - β .

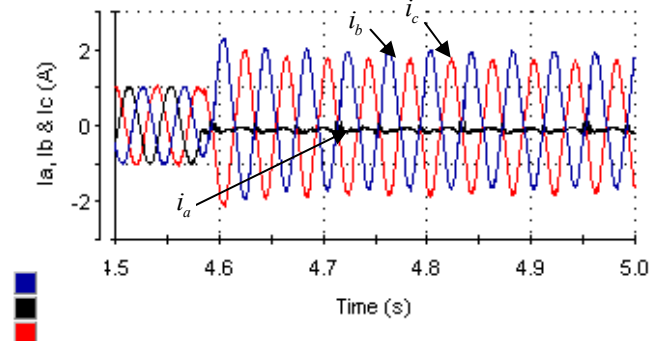


Fig. 13. Measured phase currents during open b phase winding.

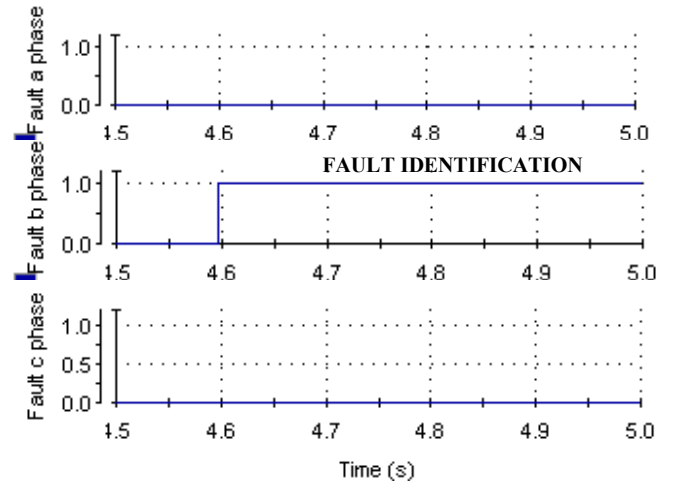


Fig. 14. Faults detection signals of stator phases.

A second test is performed in Fig.13 which presents the same waveforms that the previous test, but in this case, the open-circuit fault is applied in the phase b. Fig.14 shows the fault identification result.

Fig. 15 shows the reference and measured rotor speed with a reference one of 500 rpm. The open phase fault of phase b occurs at $t = 4.5$ sec. At time $t = 5$ s, the load torque is applied. Moreover, in this experiment, it has been observed that the phase angle of α - β axis stator currents is not affected by the load change, since it remains in the same band for permanent operating conditions, a load change and a no-load condition.

Here, it is clear that the DFT algorithm detects and identifies the faulty phases even during the load change. Therefore, it is clear that, by using this criterion, the DFT strategy can be affected during load change which then leads to false alarms.

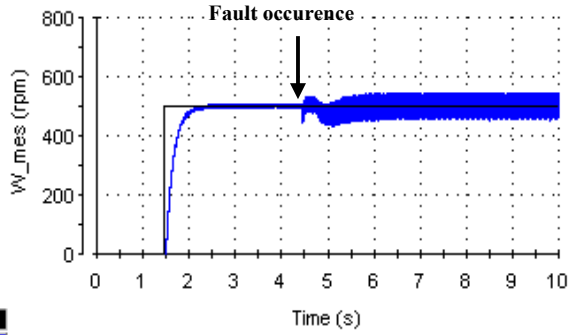


Fig. 15. Reference and measured speed.

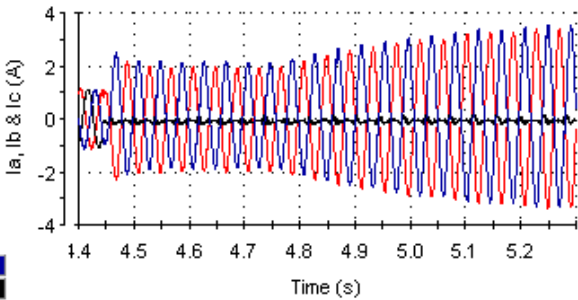


Fig. 16. Measured phase currents during open b phase winding.

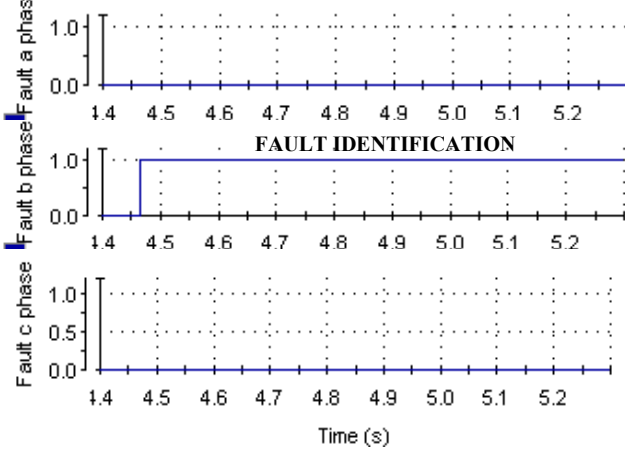


Fig. 17. Faults detection signals of stator phases.

The different 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.

IV. APPENDIX

TABLE IV

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

V. CONCLUSION

A novel approach has been proposed for the detection and localization of open-phase faults in IPMSM drives. This method is based on discrete Fourier transform phase. For this diagnosis, we developed the state space model of the PMSM expressed in the d-q synchronous reference to study the phenomena occurred in the stator current. Experimental validations are given for the open phase stator winding. Moreover, this technique uses only two current sensors. The sensors are already used in the Rotor Field Oriented Control (RFOC) of permanent magnet synchronous motor drive. The 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.

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