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Detection of Partial Demagnetization Fault in PMSMs Operating under Nonstationary Conditions

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Demagnetization fault detection of in-service Permanent Magnet Synchronous Machines (PMSMs) is a challenging task because most PMSMs operate under nonstationary circumstances in industrial applications. A novel approach based on tracking characteristic orders of stator current using Vold-Kalman Filter is proposed to detect the partial demagnetization fault in PMSMs running at nonstationary conditions. Amplitude of envelope of the fault characteristic orders is used as fault indicator. Experimental results verify the superiority of the proposed method on partial demagnetization online fault detection of PMSMs under various speed and load conditions.

Index Terms—Demagnetization, fault detection, nonstationary, permanent magnet synchronous motors (PMSMs), Vold-Kalman filtering (VKF)

I. INTRODUCTION

PARTIAL demagnetization of Permanent Magnet Synchronous Motors (PMSMs), may lead to a progressive performance degradation or even arouse catastrophic failures [1-2]. Thus, early and accurate detection of the partial demagnetization fault is of great significance for the operation & maintenance of PMSMs and associated machinery and electromechanical systems. So far, the commonly monitored parameters for Partial Demagnetization Fault Detection (PDFD) are stator current [3-5], zero sequence voltage component [6], Back-EMF [7], shaft trajectory [8] and vibration [9]. Following the classical motor current signature analysis approach, the characteristic demagnetization fault frequencies, f_d , are $f_0(1 \pm \frac{k}{P})$, where f_0 is the electrical fundamental frequency, k is an integer, and P is the number of pole pairs [3-8,10-11,13-14]. Thus, the PDFD under stationary conditions of speed and torque is commonly based on the identification of such characteristic fault frequencies throughout the spectrum analysis, estimated by means of conventional Fourier Analysis (FA) [6-8]. All frequency components of the analyzed signal could be revealed via FA, which is only suitable for analysis under stationary conditions, the frequencies changing with time could not be tracked. However, most PMSMs operate under nonstationary conditions in industrial applications. For instance, PMSMs in wind power applications rotate at variable speed in order to extract the maximum power from wind [12]. For PDFD under nonstationary conditions, classical spectrum analysis is invalid due to evident frequency aliasing. Hence, the joint time-frequency domain analysis represents the most suitable solution for PDFD under nonstationary conditions, including mainly Wavelet Transform (WT) [3, 13], Hilbert-Huang Transform (HHT) [4] and Choi-William Distribution (CWD) [14]. The WT and HHT methods are based on the analysis of

different frequency bands, however, the frequency band of the fault related orders may cross over several bands in drastic changing operation conditions, which may affect the analysis of the fault characteristics. The CWD is a good method for global time-frequency representation of the fault related signatures, however, the global representation is time consuming and unnecessary because only the characteristic fault related harmonics are required.

A novel methodology based on the tracking of the characteristic demagnetization fault orders of stator current by means of Vold-Kalman Filter (VKF) is presented for PDFD of PMSMs running under nonstationary conditions. The rest of this paper is organized as follows, section II describes the principle of VKF briefly, experimental setup of partial demagnetization of a PMSM is presented in section III, in section IV, the PDFD results under various nonstationary scenarios using the proposed VKF are presented and analyzed, section V draws the conclusions.

II. ORDER TRACKING USING VOLD-KALMAN FILTER

VKF, proposed by Håvard Vold in 1993 based on Kalman filtering, could track the multiple harmonic orders simultaneously. The advantages including ability of handling time-varying signal, no phase deviation and capability of extracting orders in time domain, make VKF based order tracking feasible for the PDFD of PMSMs under nonstationary conditions [15-16]. The principle of VKF based order tracking is briefly introduced in this section.

Suppose $\mathbf{x} = [x(1) \ x(2) \ \dots \ x(N)]^T$ is the tracked harmonic order and the differential order is 3, then structure equation is,

$$\mathbf{A}\mathbf{x} = \boldsymbol{\varepsilon} \quad (1)$$

where

$$\mathbf{A} = \begin{bmatrix} 1 & -3 & 3 & -1 & \dots & 0 & 0 & 0 & 0 \\ 0 & 1 & -3 & 3 & \dots & 0 & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & 0 & \dots & 1 & -3 & 3 & -1 \end{bmatrix},$$

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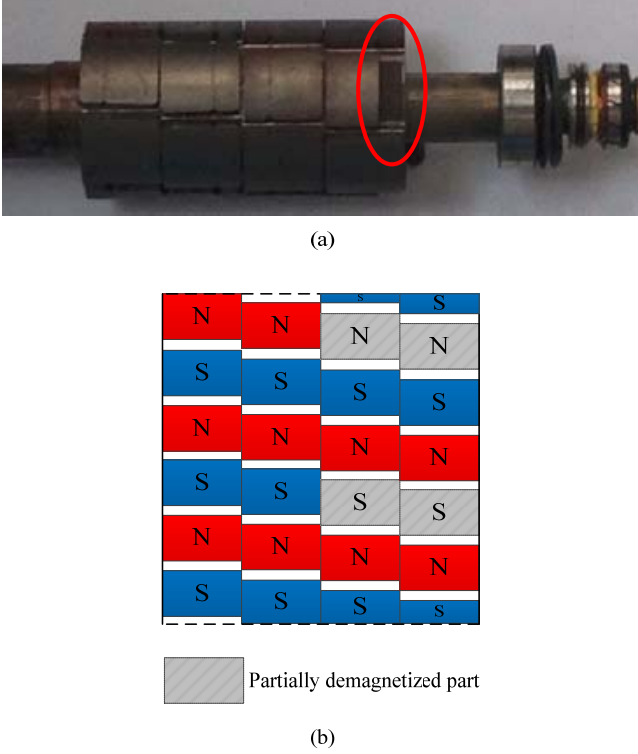


Fig. 1. Experimental setting of partial demagnetization of one pole pair. (a) Damaged magnet of a surface-mounted PMSM. (b) Schematic of 50% partial demagnetization scheme of one pole pair in the unfolded magnet array.

$\boldsymbol{\varepsilon} = [\varepsilon(1) \ \varepsilon(2) \ \dots \ \varepsilon(N-3)]^T$ is the non-homogenous term.

Data equation is,

$$\mathbf{y} = \mathbf{C} \mathbf{x} + \boldsymbol{\eta} \quad (2)$$

where $\mathbf{y} = [y(1) \ y(2) \ \dots \ y(N)]^T$ is the measurement, $\boldsymbol{\eta} = [\eta(1) \ \eta(2) \ \dots \ \eta(N)]^T$ is the measurement error and noise.

$$\mathbf{C} = \begin{bmatrix} e^{j\theta(1)} & 0 & \dots & 0 \\ 0 & e^{j\theta(2)} & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & e^{j\theta(n)} \end{bmatrix}$$

is the output matrix,

$$\theta(n) = \sum_{i=1}^n \omega(i) \Delta t \quad (3)$$

$\omega(i)$ is discrete angular frequency, Δt is sampling interval.

Based on least square method, the quadratic sum of $\boldsymbol{\varepsilon}$ and $\boldsymbol{\eta}$ should be minimum, thus the cost function

$$J = r^2 \boldsymbol{\varepsilon}^T \boldsymbol{\varepsilon} + \boldsymbol{\eta}^T \boldsymbol{\eta} = r^2 \mathbf{x}^T \mathbf{A}^T \mathbf{A} \mathbf{x} + (\mathbf{y}^T - \mathbf{x}^* \mathbf{C}^*) (\mathbf{y} - \mathbf{C} \mathbf{x}) \quad (4)$$

r is weighting coefficient, superscript $*$ stands for complex conjugate. By derivation operation, we get the tracked order,

$$\mathbf{x} = (r^2 \mathbf{A}^T \mathbf{A} + \mathbf{I})^{-1} \mathbf{C}^* \mathbf{y} \quad (5)$$

which makes cost function J minimum, where \mathbf{I} is the identity matrix.

III. EXPERIMENTAL SETUP

Experimental tests have been carried out using one healthy motor and one motor with partially demagnetized (50%) fault which is artificially introduced by special treatment. 50% demagnetization of one pole pair is a representative case between incipient and serious damaged conditions. A laboratory scale test platform has been developed which mainly consists of two identical face to face motors, one is used as tested motor and the other is acted as load. The main technical specifications of the experimental PMSMs are listed in Table I. Experimental setting of demagnetization of one pole pair is shown in Fig. 1. Damaged magnet of a surface-mounted PMSM is demonstrated in Fig. 1(a). Fig. 1(b) presents the specific locations of 50% demagnetization fault in the unfolded magnet array. Four different nonstationary operating scenarios have been investigated in this study for each tested PMSM.

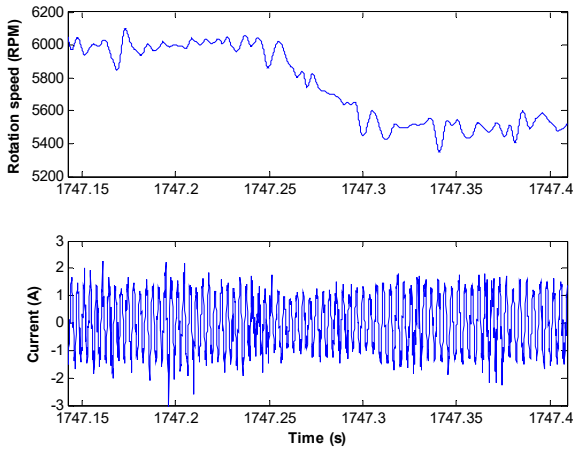
TABLE I
MAIN TECHNICAL SPECIFICATIONS OF THE EXPERIMENTAL PMSMS

Parameter	Value
Manufacturer	ABB
Power converter model	DGV 700
Rated voltage	230 Vac
Rated current	2.9 A
Rated speed	6000 r/min
Rated torque	2.3 Nm
Pole pairs	3
Stator slots	18
Nominal flux density	0.85 T

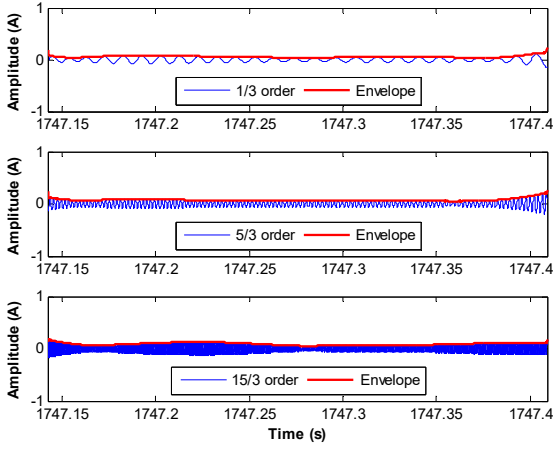
The stator currents are measured using Tektronix A622 ac/dc current probe. Sampling frequency is 12 kHz, NI DAQ PCI-6251 is used for the data acquisition. A shaft encoder is mounted on the rotor shaft of PMSM to capture the rotational speed.

IV. RESULTS AND DISCUSSION

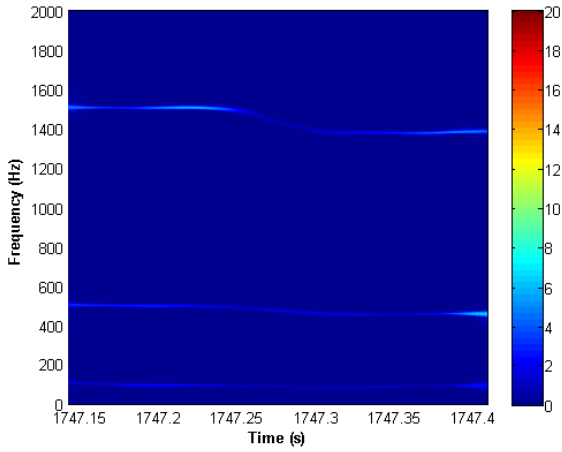
The VKF based order tracking results of the healthy PMSM with speed profile from 6000 to 5550 r/min and nominal load are shown in Fig. 2. As can be seen in Fig. 2(a), the rotational speed varies from 6000rpm to 5550rpm during about 0.3 second, consequently, mechanical foundational frequency changes from 100 Hz to 92.5 Hz. The stator current of phase A in this period is also shown in Fig. 2(b). There are three pole pairs in this machine, thus, the electrical foundational frequency f_0 changes from 300 Hz to 277.5 Hz. The 1/3, 5/3, 15/3 order harmonics are tracked successfully by using the proposed VKF based order tracking as shown in Fig. 2(c). The envelopes of the tracked order are also displayed in this figure.



(a)



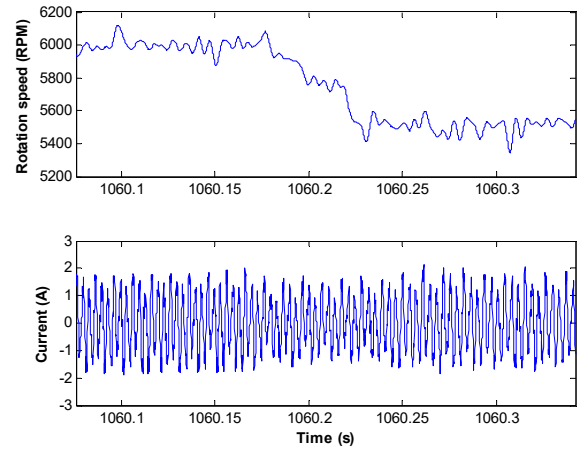
(b)



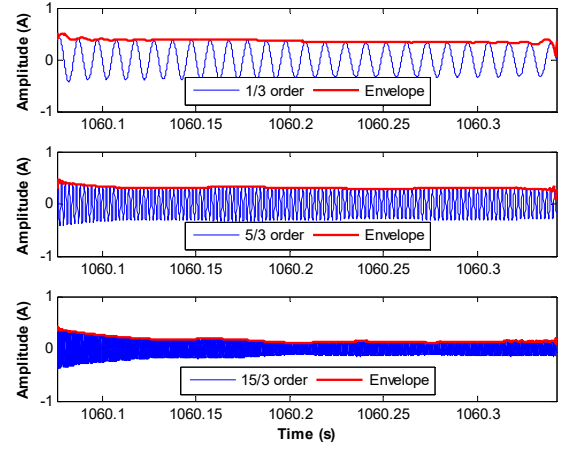
(c)

Fig. 2. PDFD results of healthy PMSM with slope speed profile from 6000 to 5550 r/min. (a) Rotational speed and stator current. (b) Tracked 1/3, 5/3 and 15/3 orders and corresponding envelopes of stator current. (c) Choi-Williams time frequency distribution of the tracked orders.

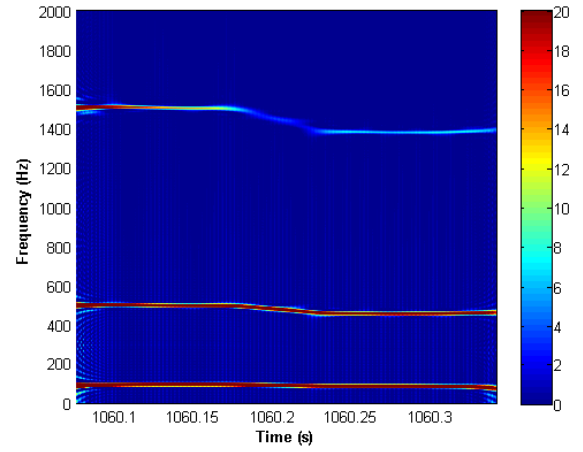
Choi-Williams time frequency distribution of the tracked three characteristic orders is demonstrated in Fig. 2(d). The corresponding results of 50% demagnetized PMSM with the same speed profile from 6000 to 5550 r/min and nominal load are presented in Fig. 3. By comparing the results in these two



(a)



(b)



(c)

Fig. 3. PDFD results of 50% demagnetized PMSM with slope speed profile from 6000 to 5550 r/min. (a) Rotational speed and stator current. (b) Tracked 1/3, 5/3 and 15/3 orders and corresponding envelopes of stator current. (c) Choi-Williams time frequency distribution of the tracked orders.

scenarios, it can be observed that the envelopes of 1/3, 5/3, 15/3 orders of stator current in 50% demagnetization fault occasion are all higher than those of healthy occasions. Significant difference of Choi-Williams time frequency distributions of the tracked orders of these two cases can be

observed easily.

TABLE II
ENVELOPE VALUE (RMS) OF FAULT CHARACTERISTIC ORDERS FOR PMSM
WITH 50% DEMAGNETIZATION OPERATING UNDER DIFFERENT SPEEDS AND
LOADS CONDITIONS

I: 6000-5550 r/min, rated load			
	$f_0/3$	$5f_0/3$	$15f_0/3$
Healthy	0.0615	0.0800	0.0961
50% demagnetization	0.3630	0.3130	0.1770
II: 6000-5550 r/min, half-rated load			
	$f_0/3$	$5f_0/3$	$15f_0/3$
Healthy	0.0585	0.0591	0.0556
50% demagnetization	0.2669	0.1952	0.0885
III: 3000-2500 r/min, rated load			
	$f_0/3$	$5f_0/3$	$15f_0/3$
Healthy	0.0566	0.0700	0.0334
50% demagnetization	0.1351	0.1283	0.0364
IV: 3000-2500 r/min, half-rated load			
	$f_0/3$	$5f_0/3$	$15f_0/3$
Healthy	0.0545	0.0387	0.0264
50% demagnetization	0.1105	0.0957	0.0275

Four operating conditions which assembles two different varying speed cases and two different load levels for each tested PMSM have been emulated in the experiments to verify the robustness of the proposed approach. The amplitudes of envelope of fault characteristic orders of stator currents for healthy and 50% demagnetization PMSMs operating under different conditions are presented in Table II. It is observed that the amplitudes of envelopes of stator currents of 50% demagnetization all increase compared with those in healthy cases. Envelope change of $f_0/3$ and $5f_0/3$ harmonics are more noticeable than that of $15f_0/3$ in all of these four conditions. Thus $1/3$ and $5/3$ orders are dominant components for extraction of fault indicator and PDFD of PMSMs. It should be noted that the fault indicators are more effective in high speed conditions, for instance, the envelope of $1/3$ order of 50% demagnetization PMSM is about six times of that in healthy PMSM in condition I, while it is only doubled in condition IV. Therefore, amplitude of the envelope is a good fault indicator. 50% demagnetization fault of a PMSM operating under various nonstationary conditions has been successfully detected using the proposed VKF based order tracking approach.

V. CONCLUSION

A novel methodology based on tracking the characteristic demagnetization fault orders of stator current by means of VKF has been proposed for the PDFD of PMSMs operating under nonstationary conditions. Only the fault related harmonics are tracked while the rest of components are removed as noise. Amplitude of envelopes of the fault characteristic orders has been used as fault indicators. The results demonstrate the potential of the proposed method for PDFD of PMSMs to be applied in industrial nonstationary applications, although the experimental machine is a

relatively high speed machine (rated rotational speed is 6000 r/min), the presented methodology for detecting demagnetization could also be applicable to low-speed machines.

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