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A Novel Method for Partial Demagnetization Fault Detection in PMSMs

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ABSTRACT: It is generally very important to detect partial demagnetization faults at the beginning stage for Permanent Magnet Synchronous Motors (PMSMs) which are generally operated under nonstationary conditions in industrial applications. In this study, a new method based on Gabor Order Tracking (GOT) has been presented which tracks the orders that are characteristic of the fault in motor current at nonstationary operating speeds for the detection of partial demagnetization fault. The amplitude changes of the envelope signal obtained from the order components were used as fault indicators. The results obtained from the experimental study indicate that the suggested method successfully detects the partial demagnetization fault under different speed and load conditions. The main innovative parts of this study are that GOT method was implemented on the motor current signal for the first time.

Keywords – *Demagnetization, Fault detection, Gabor order tracking, Nonstationary, Permanent magnets motors.*

SMSM'de Kısmi Demagnetizasyon Arızasının Tespiti için Yeni Bir Yaklaşım

ÖZET: Endüstriyel uygulamalarda genellikle durağan olmayan çalışma şartlarında çalıştırılan Sabit Mıknatıslı Senkron Motorlar (SMSM) için kısmi demagnetizasyon arızasının başlangıç aşamasında tespiti oldukça önemlidir. Sunulan çalışmada kısmi demagnetizasyon arızasının tespiti için durağan olmayan çalışma hızlarında motor akımında arızaya ait karakteristik mertebeleri Gabor Order Tracking (GOT) tabanlı izleyen yeni bir yöntem sunulmuştur. Arızaya ait karakteristik mertebe bileşenlerinden elde edilen zarf sinyalinin genlik değişimleri arıza göstergesi olarak kullanılmıştır. Deneysel çalışmada elde edilen sonuçlar önerilen yöntemin kısmi demagnetizasyon arızasını değişik hız ve yük şartlarında başarılı şekilde tespit ettiğini göstermektedir. Bu çalışmanın temel yenilikçi kısmı, motor akım sinyaline ilk defa GOT metodunun uygulanmasıdır.

Anahtar Kelimeler – *Demagnetizasyon, Hata teşhisi, Gabor order tracking, Dinamik çalışma, Sabit mıknatıslı motorlar.*

1. Introduction

Permanent Magnet Synchronous Motors (PMSMs) are frequently preferred in the industry for use in applications that require varying speeds and torques. The PMSMs faults can be classified: electrical faults (stator windings short circuits), magnetic faults (broken or demagnetization of magnets) and mechanical faults (misalignment, rotor eccentricity and bearing damages). In demagnetization fault, irreversible flux losses occurs which reduce the motor efficiency and can also produce unbalanced magnetic pull that can generate noises and vibrations on the motor core (Akar and Eker, 2013). In addition, due to airgap flux density distribution power factor changes and electromagnetic torque decrease. The main reasons for the demagnetization fault in PMSM's can be listed as; load conditions that require high starting torques, armature reaction that occurs during rapid transformations from transient state to nonstationary state, the magnetic fields in the opposite direction generated by the currents passing through nonstationary stator windings and high temperatures (Akar and Eker, 2013; Hur, 2008). Whereas the accurate detection of partial demagnetization fault at the beginning stage reduces maintenance and repair costs, it also increases the safety of the system containing the PMSM. Frequently, stator currents (Ruiz et al., 2009; Espinosa et al., 2010; Ishikawa et al., 2013), zero sequence voltage component (Urresty et al., 2012), back-EMF (Urresty et al., 2013), and vibration (Yang et al., 2014) is monitored to detect this fault. Demagnetization fault generates additional side-band components in the motor current spectrum. The positions of these components are calculated via Equation 1 (Roux et al., 2007).

$$f_{demag} = \left(1 \pm \frac{k}{p}\right) f_e \quad (1)$$

f_{demag} denotes the demagnetization fault frequency, $k = 0,1,\ldots,n$ is a constant number, p is the number of motor pole pairs and f_e is the electrical supply frequency. Monitoring the relevant frequency component obtained as a result of Fourier analysis carried out under stationary operating conditions yields successful results in fault detection. In addition, PMSMs are operated under varying speed and load conditions in many applications which change both the amplitude and frequency of the motor current. The classical spectral analysis method which is successful for stationary signals is not successful because of its insufficiency in nonstationary signals. Wavelet Transform (Roux et al., 2007), Hilbert-Huang Transform (Espinosa et al., 2010), Choi-William Distribution (Prieto et al., 2011), classical order tracking analysis (Akar and Eker, 2013), and Vold-Kalman Filter (Wang et al., 2016) methods have been used for dynamic fault signal analysis.

A novel methodology based on the tracking of the characteristic demagnetization fault orders of stator current by means of Gabor Order Tracking (GOT) is presented for partial demagnetization fault detection in PMSMs operating under three nonstationary speeds and five loads conditions. The GOT method for vibration analysis of rotating machinery is a powerful tool for machinery monitoring and fault detection due to it does not introduce phase or amplitude distortion into the extracted signal, intermediate step of order energy specification occurs in the time-frequency domain and order energy can be selected with either a constant bandwidth or with a bandwidth that varies with the rate of speed change (Anonymous, 2016).

The remainder of this paper is organized as follows, Section II describes principle of the proposed GOT method, experimental setup and data acquisition is presented in Section III, the effectiveness of the GOT is demonstrated in Section IV via experimental tests corresponding to different PMSM conditions and some concluding remarks are summarized in Section V.

2. Discreet Gabor Expansion Based Order Tracking

Order Tracking (OT) is a fundamental method used for the dynamic signal analysis of rotating machines. In this scope, many different OT methods with various advantages and disadvantages are used such as resampling OT (Gade et al., 1995), Vold-Kalman OT (Gade et al., 1999; Pan and Wu, 2007; Qian, 2003). GOT method is a method based on discrete Gabor transformation and Gabor expansion. Gabor expansion method is also known as Gabor reconstruction or synthesis (Jin and Hao, 2010).

$$\begin{aligned}\tilde{c}_{m,n} &= \sum_{i=m\Delta M-L/2}^{m\Delta M+L/2-1} s[i]\gamma^{*}_{m,n}[i] \\ &= \sum_{i=m\Delta M-L/2}^{m\Delta M+L/2-1} s[i]\gamma^{*}_{m,n}[i-m\Delta M]e^{-2j\pi ni/N}.\end{aligned} \tag{2}$$

If where $s[i]$ is the time domain signal used in Equation 2, ΔM indicates the time sampling step in the point number, M indicates the time sampling number, N shows the frequency sampling number, L shows the window length in point number, and "$*$" denotes complex conjugate operation (Jin and Hao, 2010).

According to Equation 2; the Gabor coefficients, $\tilde{c}_{m,n}$ are the sampled short-time Fourier transform with the window function $\gamma[i]$ (Jin and Hao, 2010). To apply the Fast Fourier Transform, the frequency bin, N, is set to be equal to L, which has to be a power of 2. L has to be divided by both N and ΔM. Whereas Equation 3 is used for transforming the signal acquired at the frequency domain to the time domain (Jin and Hao, 2010).

$$\begin{aligned}s[i] &= \sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\tilde{c}_{m,n}h_{m,n}[i] \\ &= \sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\tilde{c}_{m,n}h_{m,n}[i-m\Delta M]e^{-2j\pi ni/N}.\end{aligned} \tag{3}$$

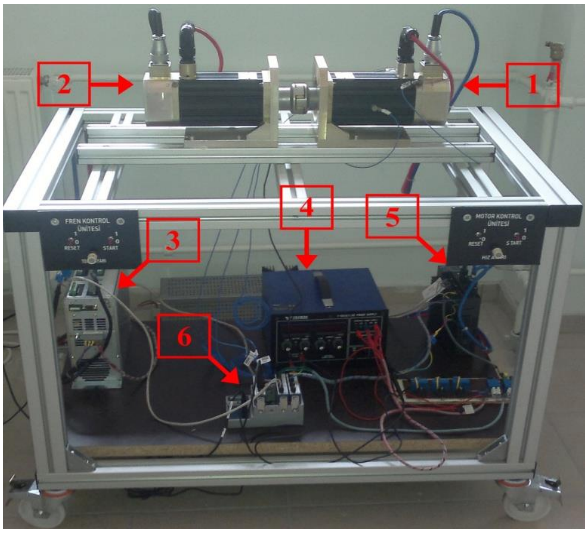
where $\{h_{m,n}[i]\}$ $m,n \in Z$ is the Gabor elementary functions, also called as the set of reconstruction functions, and $\{\gamma_{m,n}[i]\}$ $m,n \in Z$ is the set of analysis functions. $h[i]$ is the reconstruction window and $\gamma[i]$ is the analysis window.

As a result, $\{h_{m,n}[i]\}$ $m,n \in Z$ and $\{\gamma_{m,n}[i]\}$ $m,n \in Z$ are the time-shifted and harmonically modulated versions of $h[i]$ and $\gamma[i]$, respectively (Jin and Hao, 2010).

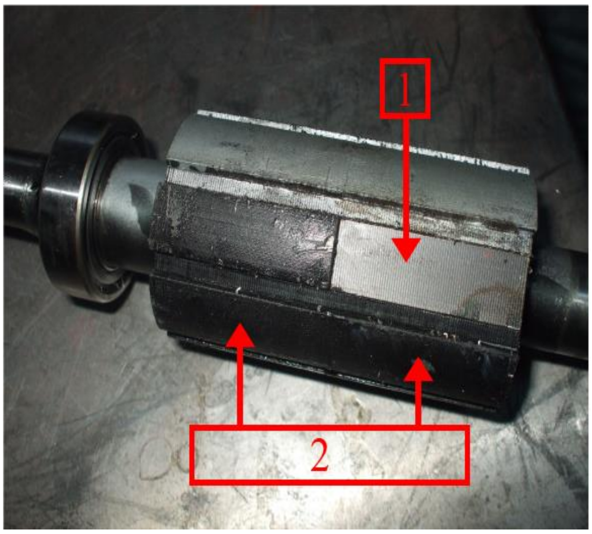
3. Experimental Setup

In the experimental study, 2 identical motors were used with a shaft power of 1.2 kW, 4 pole pairs, supply voltage of 230 V, nominal torque of 4 Nm and nominal speed of 3000 rpm (Akar and Eker, 2013). Whereas one of this motors was used as a motor in closed loop speed control mode, the other was used as a braking system in closed loop torque control mode. NI-cDAQ-9174 cabin was used for data acquisition, NI9227 module for current measurement and NI9239 module via the encoder attached to the motor shaft for speed measurement. The motor speed and current signal was measured for 10 sec with a sampling frequency of 12.8 kHz. LabVIEW Sound and Vibration Assistant Toolkit 2011 software has been used in data acquisition and GOT.

NIM-10000H coded surface mounted Nd-Fe-B magnets were used in the rotor and 2 magnets constitutes 1 pole. Demagnetization fault was generated by 2 different methods. In the first method, the 2 magnets constitutes a pole were subject to high temperatures for a period of 5 hours decreasing the magnetic flux intensity from 3.02 kGauss to 0 kGauss which was then attached to the rotor. Thus, a demagnetization fault of 12.5% occurred in the motor. Whereas in the second method, 1 magnet of the pole that is neighboring the pole demagnetized via thermal treatment of the rotor was removed and the rotor was replaced after balancing. A demagnetization fault of about 18% occurred as a result of this procedure. The experimental setup and rotor with partial demagnetization induced are shown in Fig. 1.



(a)

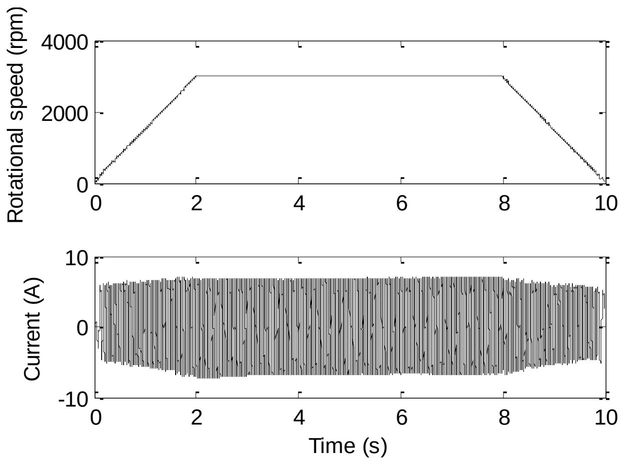


(b)

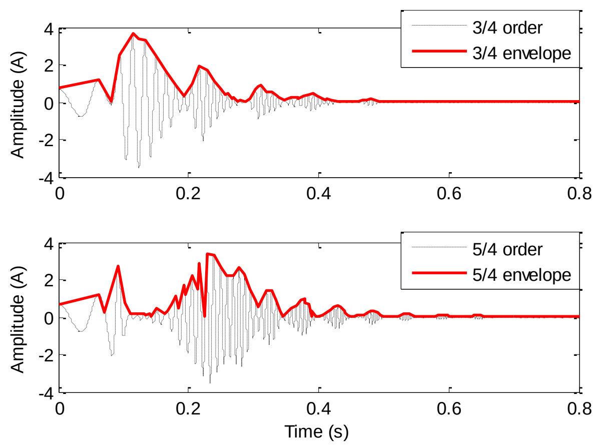
Figure 1: *(a) Experimental test rig (1: PMSM, 2: Brake, 3: Brake controller, 4: Power supply, 5: Motor controller, 6: Data acquisition board). (b) Damaged magnets of surface-mounted PMSM (1: Removed Magnet, 2: Thermally demagnetizated magnets).*

4. Result and Discussion

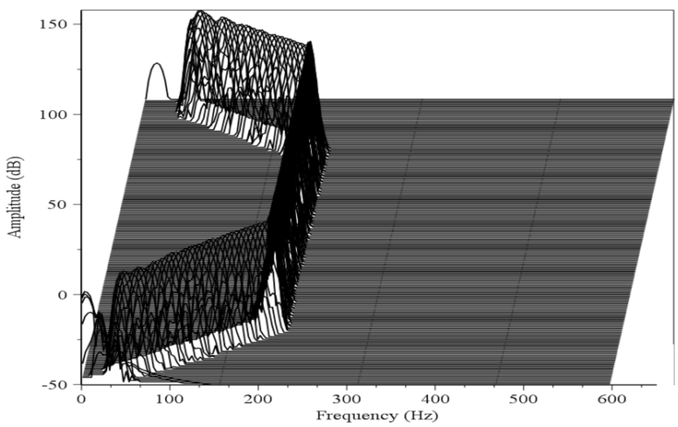
The curves obtained via GOT for operating PMSMs at an operating speed of 0-3000-0 rpm and at nominal load are shown in Fig. 2.



(a)



(b)



(c)

Figure 2: *GOT results for healthy PMSM with speed profile 0-3000-0 r/min. (a) Rotational speed and stator current. (b) Tracked 3/4 and 5/4 orders and corresponding envelopes of stator current. (c) Waterfall graph of the tracked orders.*

As can be seen in Fig. 2(a), the motor speed increases from 0 to 3000 rpm in 2 seconds thus increasing the motor electrical supply frequency from 0 Hz to 200 Hz. The PMSM used has 4 pole pairs. Therefore, it is expected that the most distinctive order components related with the fault to appear at the 3/4 and 5/4 times of the fundamental order. Fig. 2(b) shows the 3/4 and 5/4 order components and the envelopes acquired via GOT.

The results obtained for PMSM with partial demagnetization fault under the same operating conditions are shown in Fig. 3. When Fig. 3 is examined, amplitude increase is observed in 3/4 and 5/4, 7/4 and 9/4 order components due to the fault. However, the most distinctive amplitude change is observed in the lower and upper sidebands of the fundamental order component.

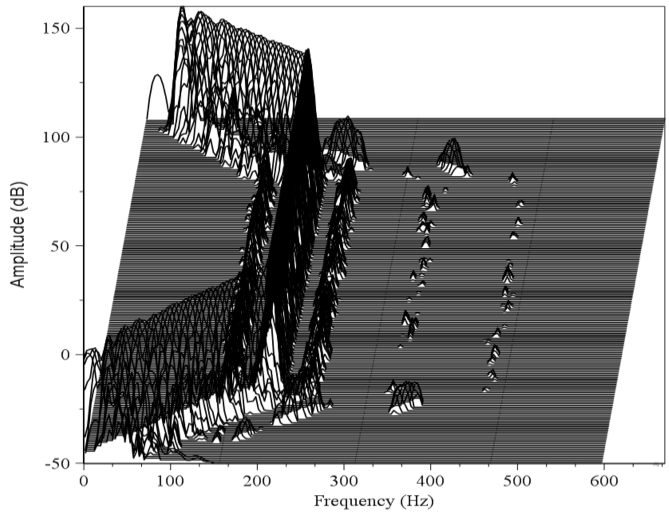


Figure 3: *Waterfall graph of PMSM under 18% demagnetization fault.*

The changes in the rms amplitude of the envelope signal acquired at the 25%, 50%, ..., 125%, 3/4 and 5/4 orders at the same operating speed and 5 different load conditions are given in Fig. 4.

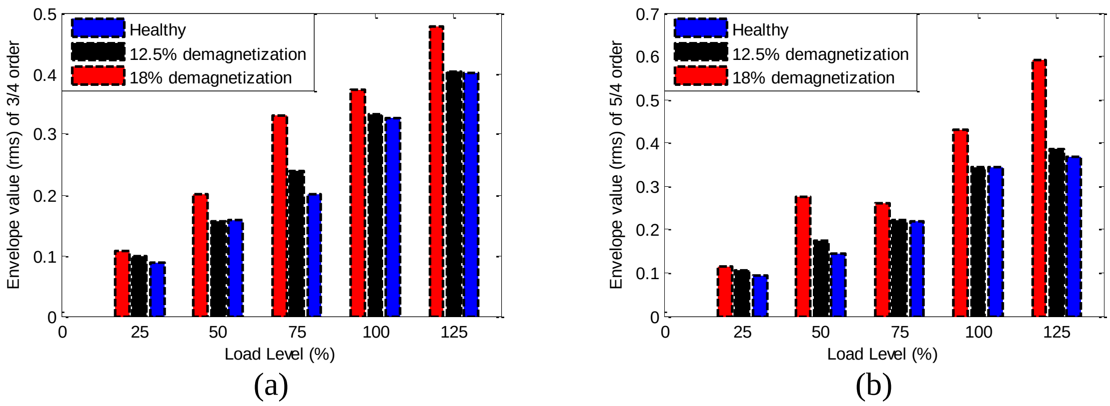


Figure 4: *Envelope value (rms) of fault characteristic orders for PMSM with partial demagnetization fault under different load levels. (a) Tracked 3/4 order envelope value. (b) Tracked 5/4 order envelope value.*

When Fig. 4 is examined, the operating and faulty states for both 3/4 order and 5/4 order can be distinguished. In addition, this difference can be seen clearer with load increase.

Table 1: *Envelope value (rms) of related fault characteristic orders under different speeds and load conditions.*

0-750-0 r/min speed profile						
Load (%)	3/4 order envelope value			5/4 order envelope value		
	Healthy	12.5% demag.	18% demag.	Healthy	12.5% demag.	18% demag.
25	0.3244	0.3430	0.4273	0.4692	0.4881	0.5366
50	0.6744	0.6919	0.7442	0.8584	0.8959	0.8584
75	0.9062	0.9452	1.0585	1.1426	1.2327	1.2565
100	1.2875	1.2994	1.3342	1.5284	1.5606	1.6509
125	1.4931	1.7793	1.8190	1.6891	1.9055	1.9027
0-1500-0 r/min speed profile						
Load (%)	3/4 order envelope value			5/4 order envelope value		
	Healthy	12.5% demag.	18% demag.	Healthy	12.5% demag.	18% demag.
25	0.1839	0.1985	0.2285	0.2392	0.2102	0.2585
50	0.3386	0.3699	0.4141	0.3389	0.4437	0.4815
75	0.4398	0.4765	0.5524	0.5529	0.5746	0.6552
100	0.5379	0.5795	0.6194	0.7712	0.8301	0.8992
125	0.6926	0.6906	0.8255	0.8486	0.9489	0.9553

The envelope values obtained from the order components of the fault under different speed and load values are given in Table 1. The amplitude change for 3/4th order at 0-750-0 rpm operating speed, full load value and 18% partial demagnetization fault in comparison with the fully operating state is 3.63%, whereas the amplitude change for 5/4th order is 8.55%. Whereas these values are 15.15% and 16.60% for 0-1500-0 rpm respectively, they are 17.91% and 24.91% respectively for 0-3000-0 rpm. As can be seen from the obtained results, the suggested method is successful in detecting the partial demagnetization fault at low, moderate and nominal speeds. In addition, it is also observed that the % amplitude change increases with increasing speed thus making fault detection easier.

5. Conclusion

A new GOT based method for monitoring the fault related order components in the stator current has been presented for the detection of partial demagnetization fault in PMSM under nonstationary operating conditions. Whereas only the fault related harmonics are monitored in the presented method, the remaining components have been removed as noise. The rms value of the envelope signal acquired from the order components of the fault were used as an indicator the detection of partial demagnetization fault. The results obtained as a result of the experimental study carried out put forth that the suggested method can easily detect partial demagnetization fault at low, moderate and nominal speeds and under differing load conditions while also showing that the suggested method is more successful at high speeds. The prominent advantages of the GOT method is that it does not bring any additional cost for the user for the reason that in inverter driven systems, current and speed sensor coexist in the system. Without requiring an additional hardware, additional software to be added to the driver software can bring driving ability to the inverter as well as the ability of online motor monitoring and fault detection. This will reduce the maintenance costs while increasing the safety of the plant and the productivity.

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