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Sabit Mıknatıslı Senkron Motorlarda Demagnetizasyon Arızasının Tespiti için Yeni bir Yaklaşım

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Özet

Elektrik motorları arızaları üretim kapasitesini düşürmekte ve bakım maliyetini yükseltmektedir. Günümüzde gerçek zamanlı durum izleme ve arıza teşhisine dayalı öngörülü bakım, periyodik uygulamaların yerini almaktadır. Bu çalışmada, **S**abit **M**ıknatıslı **S**enkron **M**otorlarda (SMSM) demagnetizasyon arızasının tespiti için yeni bir yöntem önerilmiştir. Önerilen çalışmada, mıknatısları rotor yüzeyine yerleştirilmiş SMSM' nin durağan ve dinamik çalışma koşullarında motor faz gerilimi üzerinde demagnetizasyon arızasının etkisi Mertebe Takip Analiz Yöntemi (MTA) ile incelenmiştir. Önerilen yöntem durağan ve dinamik çalışma koşullarında demagnetizasyon arızasının tespitinde başarılı olmuştur. Deneysel sonuçlar, arızaya ait frekans bileşenlerinin temel frekansın sağında ve solunda belirli mertebe seviyelerinde oluştuğunu göstermiştir. Soldaki mertebeler: birinci ve üçüncü mertebelerdir, sağdaki mertebeler beşinci ve yedinci mertebelerdir. Önerilen yöntemin etkinliği üç farklı çalışma hızı ile ispatlanmıştır. Bu çalışmanın temel yenilikçi kısmı, MTA ilk defa SMSM faz gerilimine uygulanmasıdır.

Anahtar Kelimeler :Demagnetizasyon, hata teşhisi, sabit mıknatıslı senkron motor.

A Novel Approach for Demagnetization Fault Diagnosis in Permanent Magnet Synchronous Motors

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Abstract

Electric motor faults decrease production capacity and increase maintenance cost. Nowadays, the predictive maintenance including online monitoring and predictive detection of the failures takes the place of the traditional periodic maintenance. In this study, a new method was proposed for demagnetization fault diagnosis in **P**ermanent **M**agnet **S**ynchronous **M**otors (PMSM). Surface mounted PMSM was used and the effect of a demagnetization fault on phase voltage signal of the motor operating at stationary and non-stationary speeds was examined with the help of **A**ngular **D**omain - **O**rder **T**racking (AD-OT) method. The proposed method has successfully diagnosed the demagnetization fault at both stationary and non-stationary conditions. The experimental results have shown that the frequencies of failure were determined on the left and right of fundamental frequency in the certain orders. Orders on the left were first and third order, orders on the right were fifth and seventh order. The effectiveness of the suggested method has been proven by means of three different operating speed results. The main innovative part of this study is that AD-OT method has been implemented on the PMSM phase voltage for the first time.

Keywords: Demagnetization, faultdiagnosis, permanentmagnetsynchronousmotors .

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1. Introduction

Permanent Magnet Synchronous Motors (PMSMs) are preferred more in servo systems compared to the other motors because of their superiorities such as high torque in smaller bodies, high efficiency, perfect positioning sensitivity and speed control, low moment of inertia, no need for external cooling, and over-load capability. Failures in these motors, which are an important part of the production process, both decrease the production capacity and increase the maintenance cost [1]. So it is very important to monitor the motor condition. PMSM faults can be classified as magnetic fault (demagnetization), electrical faults (winding and drive), and mechanical faults (eccentricity and bearing) [2].

Demagnetization fault in PMSMs is generally caused by load cases requiring high starting torque, armature reaction that occurs during the fast transitions from non-stationary to stationary condition, backward magnetic fields that the currents passing through the stationary stator windings generate and high temperatures appearing in the winding faults [3-4]. As a result of the demagnetization fault, irrevocable losses occur in flux produced by the magnets; which leads to a decrease in motor efficiency and the developed torque [5]. In addition to this, an increase of vibration and noise in motor body is observed because of the unbalanced magnetic pulls stemming from the demagnetization fault.

PMSMs are generally preferred in systems that require high starting torque, dynamic speed and dynamic torque. But these working conditions lead to armature reaction or extreme temperature rise in motor, thus, to formation of a partial demagnetization fault. Motor with partial demagnetization fault draws higher currents from the nominal current value while operating due to the closed loop driven, and the winding temperature increases more and more in the meantime [6]. High temperature appearing during the short-circuit faults that occur in windings results in permanent deformations in motor magnets. The average motor torque value has a decrease of 16% when the operating temperature of the magnet is raised to 140 degrees Celsius and then reduced again to the operating temperature [7].

One other reason of demagnetization fault is the longitudinal and transverse fractures and cracks on the magnets. This situation generally stems from improper and lacking production. Those cracks and fractures on the magnets cause unbalanced magnetic pull, noise and vibration in the motor [6].

Order Tracking Analysis (OTA) is one of the methods that are frequently used for monitoring the rotating machines. One of the most important advantages of OTA method with respect to the other methods used for the analysis of vibration signals is that it yields successful results in non-stationary signals whose frequency and amplitude change according to time [8]. Additional data is necessary for non-stationary signals compared to the stationary signals in order to gain successful results in the analysis of non-stationary signals. The most important one of those data is measuring the motor speed information through the encoder in the most correct way. Many researchers have developed various different methods for OTA in recent studies [9-15].

The aim of this study was to determine demagnetization fault in PMSM operating at stationary and non-stationary speeds with the help of AD-OT method. The method was applied to the dynamic phase voltage signal and the obtained experimental results were compared with the classical FFT results.

2. Materials and Methods

2.1.Demagnetization Fault

Demagnetization fault has been studied in detail by many researchers with different methods in literature [3-5, 16-25]. In those studies, it has been observed that demagnetization fault produces harmonics in motor current, voltage and electromagnetic torque signals; and that those harmonics could be detected as rotor frequency and its multiples in the electromagnetic torque spectrums; and their places could be detected with Equation 1 in current and voltage spectrums.

$$f_{de} = \left[1 \mp \frac{k}{p}\right] f_e \tag{1}$$

In this equation, f_{de} represents the demagnetization fault frequency, k represents the constant number ($k = 0,1,..,n$), p represents the motor pair of poles, and f_e represents the electrical supply frequency. Most of the studies in literature are on the analysis of the motor stationary signals. However, PMSM is generally operated at non-stationary described run-up and run-down speeds. That means a constant change in motor current, voltage, speed and torque signals according to time. FFT that yields successful results in the stationary signals is inadequate in the non-stationary signals because it doesn’t include information about time.

2.2. Angular Domain Order Tracking Analysis

In this experimental study, the AD-OT method was used. Many limitations of FFT-based methods can be overcome with this method. In AD-OT method, stationary angular intervals are sampled in consideration of constant Δt sampling time. The time sampled with constant Δt sampling is transformed into equal angular intervals with the interpolation algorithm. These times of equal angular intervals are calculated by processing the encoder signal. After the sampling, it is decided what the time-domain counterpart of the data will be [9]. The steps for the transformation from time domain to angular domain are shown in Figure 1 [9].

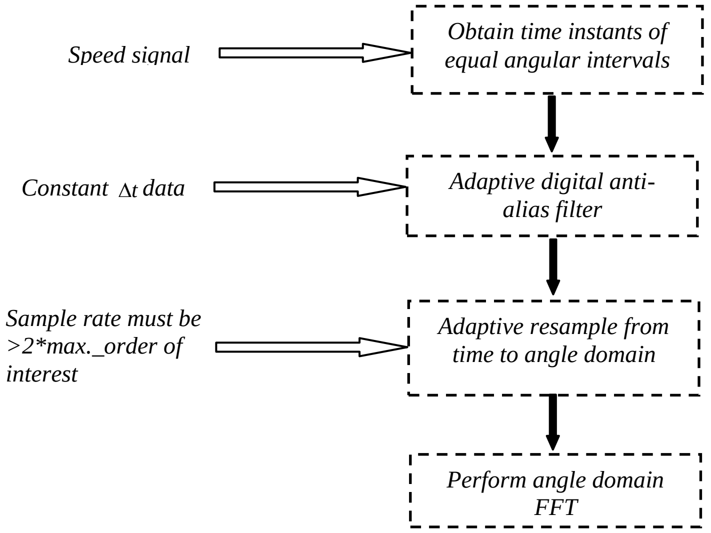


Figure 1. Flow Chart of Angular Domain Order Tracking Analysis

The data that are transformed into angular-domain are processed according to FFT and DFFT transformation [9]. As long as the transformations occur on the angular-domain data, output spectral lines represent the constant rates. This means that there are equivalent sampling relationships in consideration of time/frequency sampling relationship in angle/order domain. These equivalent sampling relationships are given in Equation 2.

$$\begin{aligned} \Delta_0 &= \frac{1}{R} = \frac{1}{N * \Delta\theta} \\ O_{nyquist} &= O_{\max} = \frac{O_{sample}}{2} \\ O_{sample} &= \frac{1}{\Delta\theta} \end{aligned} \tag{2}$$

In Equation 2, Δ_0 represents the order resolution of output order spectrum, R represents the total number of the analyzed values, N total number of the time points on the transformations, $\Delta\theta$ the angular interval of re-sampled samples, O_{sample} the angular sample at the time of data sampling, $O_{nyquist}$ Nyquist sample, and finally O_{max} represents the maximum sample that can be analyzed. Sampling relations given in Equation 2 show similarities with the FFT analysis sampling conditions given in time domain. Order resolution, Δ_0, is the reverse of the number of the analyzed transformations. That means that the analysis should be applied on several resolutions for a better order resolution. Maximum order to be analyzed can be found with the number of samples corresponding to one cycle or with the angular sampling rate. Angular-domain kernels of the transformations are given in Equation 3 [10].

$$\begin{aligned} a_m &= \frac{1}{N} \sum_{n=1}^{N} x(n\Delta\theta)\cos(2\pi o_m n\Delta\theta) \\ b_m &= \frac{1}{N} \sum_{n=1}^{N} x(n\Delta\theta)\sin(2\pi o_m n\Delta\theta) \end{aligned} \tag{3}$$

In Equation 3, the expressions o_m, a_m and b_m represent respectively the followings: analyzed order, Fourier coefficient belonging to cosine expression for o_m, and Fourier coefficient belonging to sinus expression for o_m. At the end of the transform, the x axis is no longer defined as frequency but as order and the location of any frequency on the order axis is determined via Equation 4.

$$Order = \frac{Frequency * 60}{n_r} \tag{4}$$

where n_r is the rotor speed.

2.3. Experimental Study

The experimental study is explained in this section. In the experimental study, three identical motors with a shaft power of 1.2kW, 8 poles, 230 VAC, nominal torque of 4 Nm and nominal speed 3000 rpm were used. Two of the motors were used in closed loop speed control mode (for healthy and faulty) whereas the other one was used as a brake in the closed loop torque control mode. The experimental setup and equipment can be seen in Figure 2.

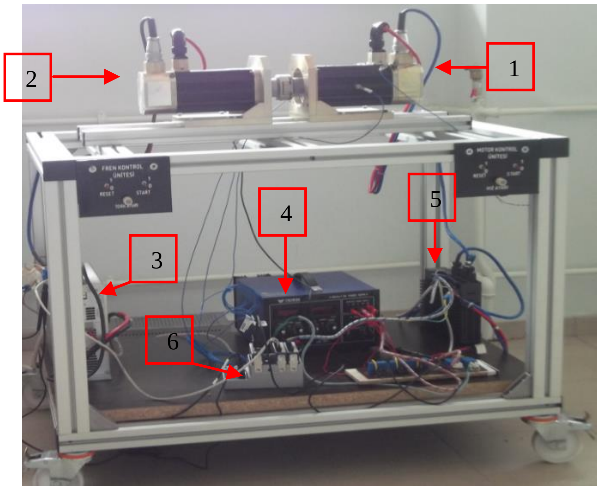


Figure 2. Experimental test rig (1:PMSM, 2:Brake, 3:Brake controller, 4:Power supply, 5:Motor controller, 6: Data acquisition board)

Demagnetization fault was created in two different methods during the experimental study. In the first method, the two magnets forming one pole were subject to heat treatment. The magnets were heated at 200 degrees Celsius for a period of 5 hours decreasing the magnetic flux density from a value of 3.02 *kGauss* to 0 *kGauss* and then they were fixed to the rotor. Thus, the motor was operated as with 7 poles and a demagnetization fault of 12.5 % was obtained. The flux densities of the magnets were measured using the Gauss/Tesla Meter (Model 5070) device of F.W.BELL company along with Standard Transverse Probe prior to and after the heat treatment process.

Whereas in the second method, one magnet of the pole neighboring the demagnetized pole (with first method) was removed and the rotor was installed again after a rebalancing. Following this operation, a total of 1.5 poles were demagnetized (a demagnetization fault of about 18 %) and the motor was operated as having 6.5 poles. The rotor subject to demagnetization fault can be seen in Figure 3.

(a)

(b)

(c)

Figure 3. Used rotors (a-Healthy, b-Under 12.5% demagnetization, c-Under 18% demagnetization).

In the experimental study, data acquisition process was carried out in two stages, namely stationary and non-stationary. In the stationary study, PMSM was operated with constant speeds of 750 rpm (50 Hz), 1500 rpm (100Hz) and 3000 rpm (200 Hz) and under a load of 100 % for each speed value after which phase voltage and rotor speed were monitored. Whereas in the non-stationary study, PMSM was subject to run-up and run-down ramps of 0-750-0 rpm, 0-1500-0 rpm and 0-3000-0 rpm for which phase voltage and rotor speeds were monitored for load values of 0 %,25%,..,125 %.

Data acquisition process was carried out using CDAQ-9174 module, NI9239 voltage module and LEM LV25P voltage sensor for a period of 10 seconds and with a sampling frequency of 25600 Hz. The motor speed was measured as TTL signal from the encoder outlet socket located on the motor drive. LabVIEW Sound and Vibration Assistant Toolkit 2011 software was used for data acquisition and FFT, AD-OT analysis.

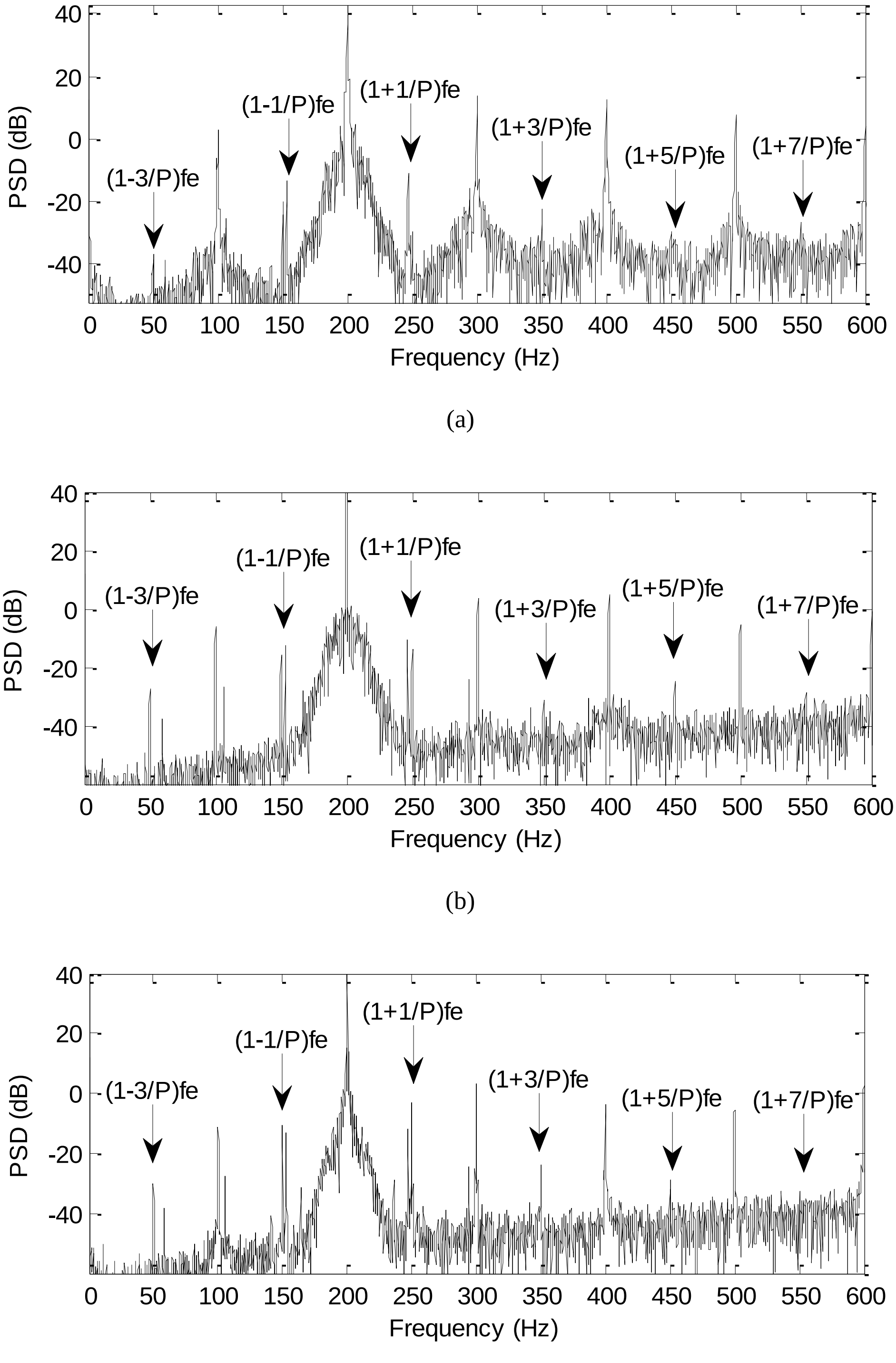
3. Results and Discussion

3.1. Analysis Results

In the presented experimental study, the monitored phase voltage was analyzed for stationary and non-stationary speeds using FFT and AD-OT methods and the obtained results have been presented below.

Operating Under Stationary Speed Conditions

PMSM was operated at values of 750 rpm (50 Hz) , 1500 rpm (100 Hz) and nominal speed of 3000 rpm (200 Hz) under 100 % load conditions and the effect of the fault on the phase voltage FFT and AD-OT spectrums was examined. Figure 4 shows the FFT spectrums obtained for 3000 rpm.



(a)

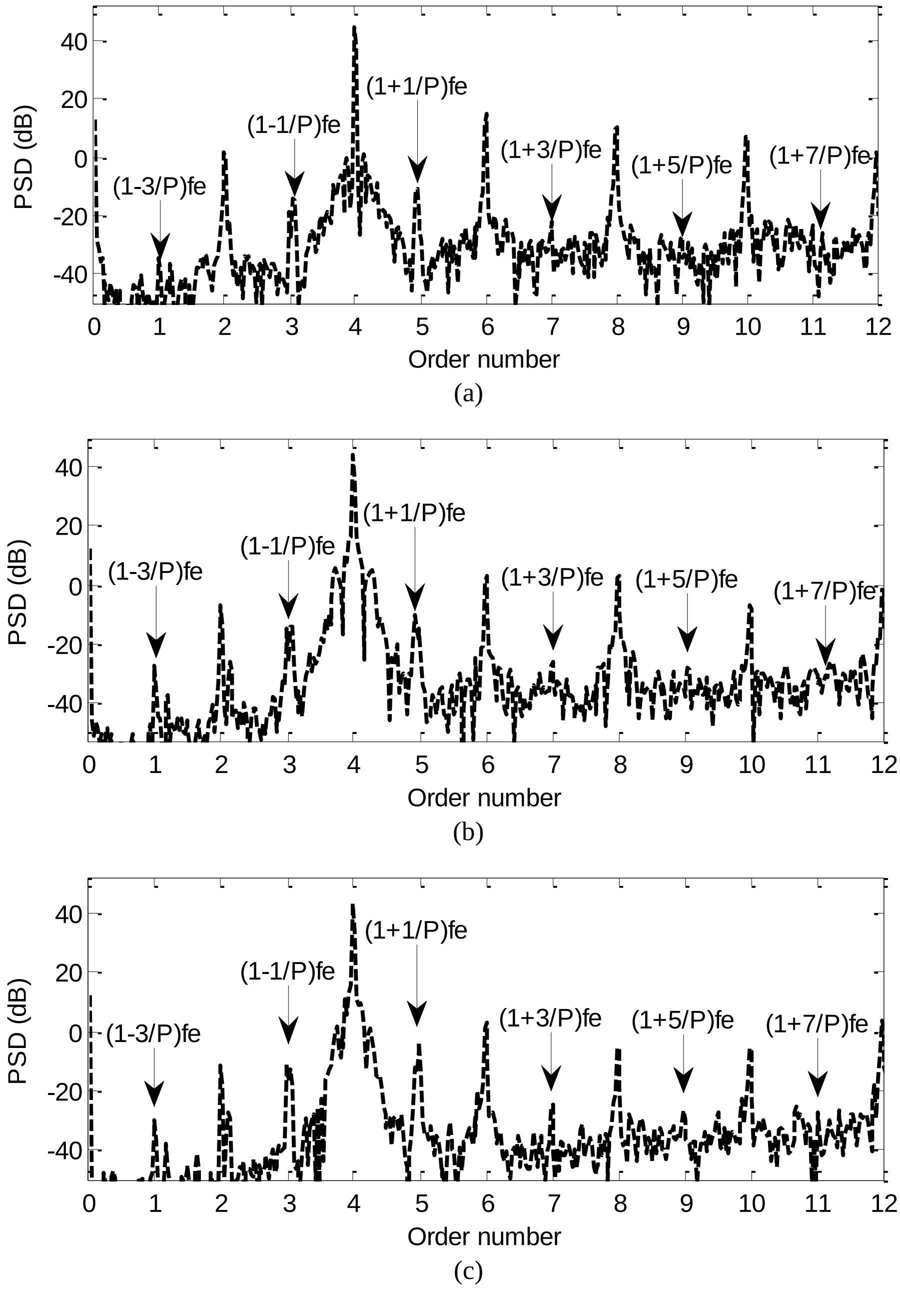
(b)

(c)

Figure 4. Motor phase voltage signal FFT spectrums operating at 3000 rpm and %100 load(a-Healthy, b-Under 12.5% demagnetization, c-Under 18% demagnetization)

When Figure 4 is examined, additional frequency components can be seen at 50 Hz ((1-3/P)fe), 150 Hz ((1-1/P)fe), 250 Hz ((1+1/P)fe), 350 Hz ((1+3/P)fe), 450 Hz ((1+5/P)fe) and 550 Hz ((1+7/P)fe) frequencies to the left and right of the fundamental frequency in accordance with Equation 1. In addition, the increase of the fault and the amplitude at these frequency components can be observed. In the PMSM rotor speed varies continuously based on the frequency of the voltage applied to the motor coils. This causes continuous change in the electrical supply frequency along with the location of the frequency components of the demagnetization fault. The location of any frequency component on the frequency spectrum is calculated using Equation 4. Since in the presented method, the voltage applied to the motor coils is re-sampled according to the rotor speed, electrical supply frequency and the frequencies of the fault components will always be at the same order levels regardless of the frequency of the voltage applied to the motor coils.

Figure 5 shows the amplitude changes in the order levels for the PMSM operating at 3000 rpm under 100% load for healthy along with 12.5 % and 18 % demagnetization faults.



(a)

(b)

(c)

Figure 5. Motor phase voltage signal AD-OT spectrums operating at 3000 rpm and %100 load (a-Healthy, b-Under 12.5% demagnetization, c-Under 18% demagnetization)

When Figure 5 is examined, it can be seen that there are severe amplitude changes especially in 3rd and 5th order levels for healthy and 18 % demagnetization fault states. Whereas the amplitude change in 3rd order level increased from -14dB to -10dB for 3000 rpm, at 1500 rpm this value increased from -22 dB to -11 dB and at 750 rpm amplitude level increased from -22 dB to -7 dB. Whereas in 5th order level, this change for 3000 rpm was from -11 dB to -3 dB, for 1500 rpm from -17 dB to -4 dB and for 750 rpm from -17 dB to -3 dB. When AD-OT spectrum results are examined, it can be observed that the fault can be clearly identified for healthy and faulty cases and that the change in amplitude increased according to the status of the fault. In addition, it was also observed that demagnetization fault caused a greater change in amplitude at 750 rpm in comparison to 1500 and 3000 rpm.

Operating Under Non-stationary Speed Conditions

In this section, PMSM was subject to predefined acceleration and deceleration ramps of 0-3000-0 rpm, 0-1500-0 rpm and 0-750-0 rpm and the FFT and AD-OT results for the non-stationary voltage signal were compared. Figure 6 shows the voltage/time and speed/time graphs for the PMSM operating under 100 % load at 0-3000-0 rpm.

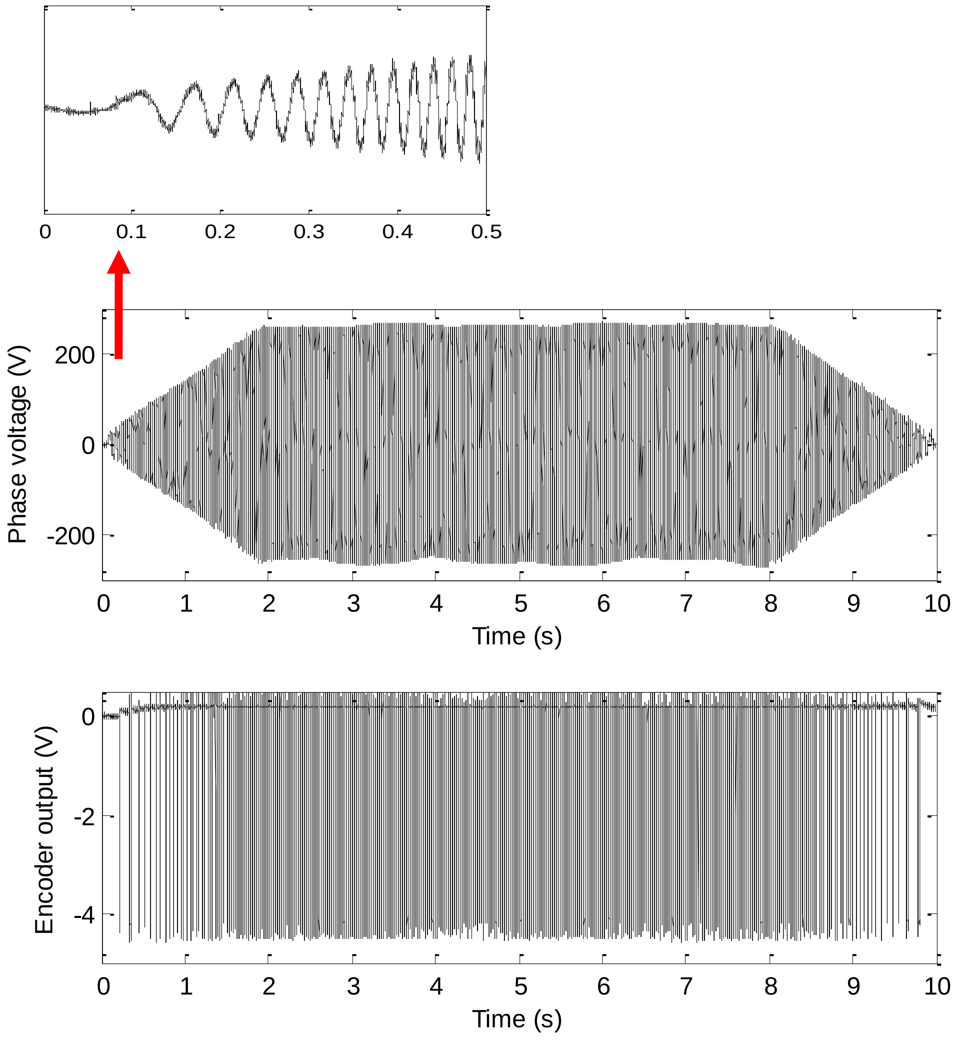
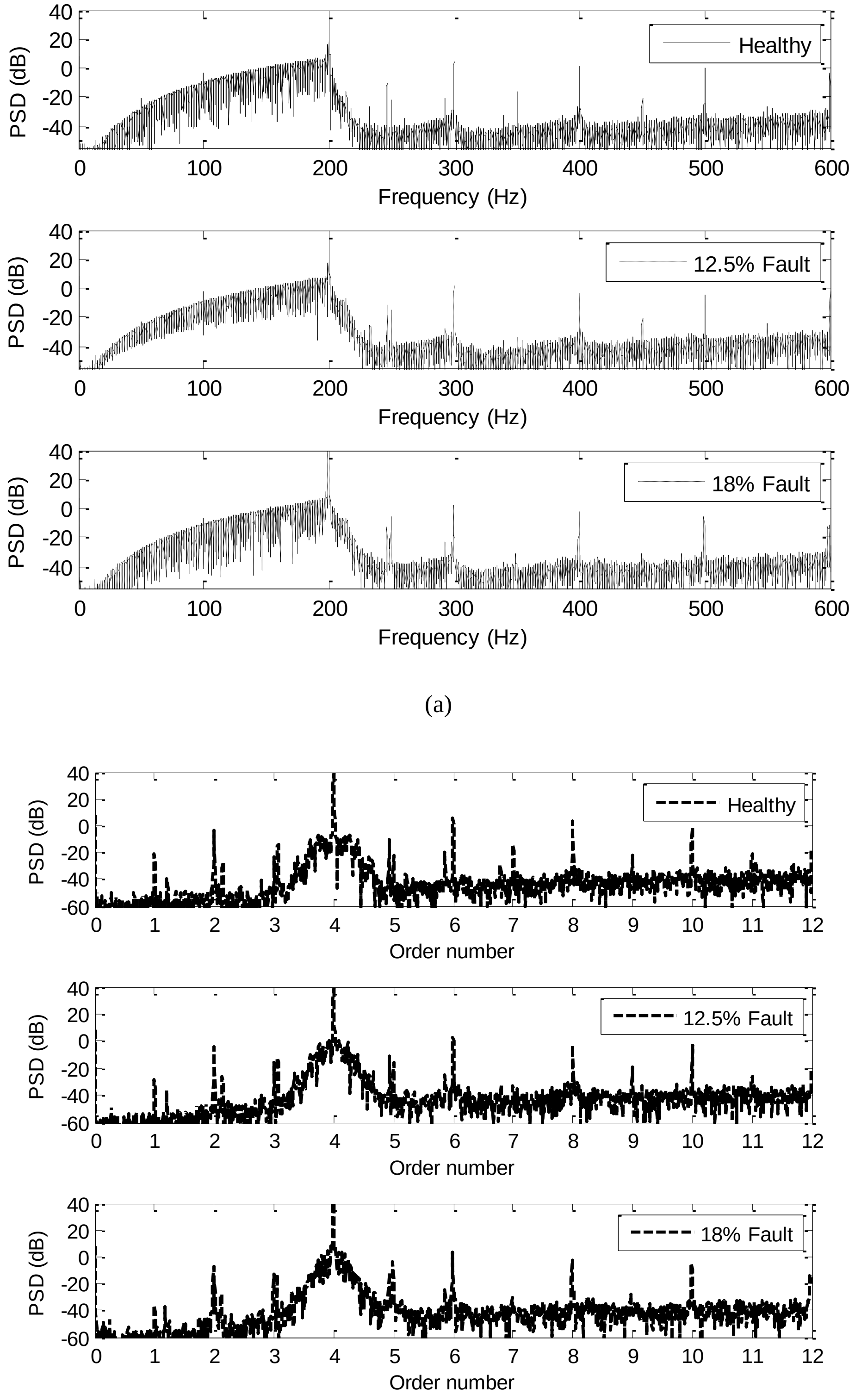


Figure 6. Motor phase voltage and speed versus time signals operating at 0-3000-0 rpm and %100 load

In Figure 6; it is observed that the amplitude and frequency of phase voltage at acceleration and deceleration regions is non- stationary.



(a)

(b)

Figure 7. Motor phase voltage FFT and AD-OT spectrums operating at 0-3000-0 rpm and %100 load (a-FFT spectrums, b-AD-OT spectrums)

In Figure 7; whereas the FFT results obtained during the analysis carried out on non-stationary signal yielded no information regarding the fault, AD-OT spectrum results contained more concise information regarding the fault as was the case in the stationary study. This is due to the fact that the presented method re-samples the non-stationary signal according to speed thereby causing it to become stationary. In the non-stationary speed conditions, experimental study was repeated for 0-1500-0 and 0-750-0 rpm under 0%-125% load conditions and the obtained values have been given in Table 1.

Table 1. 3th and 5th orders amplitude variations under non-stationary speeds [a) 0-750-0 rpm, b) 0-1500-0 rpm, c) 0-3000-0 rpm]

Load Level (%)	3th Order (dB)			5th Order (dB)		
	Healthy	12.5% Fault	18% Fault	Healthy	12.5% Fault	18% Fault
0	-20.24	-14.50	-6.80	-17.47	-10.85	-44.93
25	-21.94	-15.59	-7.07	-19.60	-12.37	-3.67
50	-21.43	-16.12	-6.14	-19.12	-13.20	-3.00
75	-22.68	-15.62	-3.78	-20.87	-12.89	-1.55
100	-23.70	-15.53	-2.37	-22.55	-12.98	-0.54
125	-13.43	-19.15	-4.56	-10.46	-40.01	-1.96

(a)

Load Level (%)	3th Order (dB)			5th Order (dB)		
	Healthy	12.5% Fault	18% Fault	Healthy	12.5% Fault	18% Fault
0	-26.96	-14.76	-12.98	-19.76	-11.12	-5.41
25	-25.39	-15.32	-12.82	-21.34	-11.82	-5.38
50	-27.83	-15.30	-12.69	-24.08	-12.10	-5.41
75	-31.05	-14.25	-12.08	-22.27	-11.45	-5.09
100	-31.23	-13.65	-11.41	-22.50	-10.72	-4.58
125	-19.78	-12.58	-11.21	-22.47	-10.02	-4.33

(b)

Load Level (%)	3th Order (dB)			5th Order (dB)		
	Healthy	12.5% Fault	18% Fault	Healthy	12.5% Fault	18% Fault
0	-23.74	-14.92	-21.78	-22.03	-12.73	-6.75
25	-19.79	-17.44	-16.01	-27.47	-12.68	-4.90
50	-19.30	-15.84	-12.98	-25.51	-16.95	-3.94
75	-19.05	-15.53	-12.61	-34.07	-16.13	-5.12
100	-20.49	-14.06	-11.56	-17.77	-13.38	-3.65
125	-12.80	-15.83	-11.88	-10.41	-13.92	-3.14

(c)

In Table1; the obtained results are in parallel with the amplitude change results obtained during the stationary study. As can be seen in the table, the amplitude changes for 0-750-0 rpm at 3rd order level is greater in comparison with other study conditions. For instance, whereas the amplitude changes for 0-750-0 rpm study with no load and for12.5 % and 18 % demagnetization states were 28.36 % and 66.40 % respectively; the same values for 0-1500-0 rpm were 45.25 % and 51.85 % and for 0-3000-0 rpm they were 37.15 % and 8.26 %. Whereas for the 0-750-0 rpm, the amplitude changes under 100% load and 12.5 % and 18 % demagnetization states were 34.47% and 90.02%, 56.26 % 63.46 % for 0-1500-0 rpm and 31.38 %, 43.58 % for 0-3000-0 rpm. The amplitude changes for the fifth order level are in parallel with those of the 3rd order level.

4. Conclusions

In the presented study, the effect of demagnetization fault on the motor phase voltage of 8 pole surface mounted PMSM has been examined. Due to the fact that PMSMs are commonly preferred in servo systems and that these systems are non-stationary; the current drawn from this motor and the applied voltage are also non-stationary. Even though FFT, which is the most commonly known method for motor fault diagnosis, gives successful results for stationary signals, it is insufficient for non-stationary signals as can be deduced from the results obtained. The method presented in this study has overcome this disadvantage by re-sampling the monitored signal according to speed and has successfully diagnosed the demagnetization fault for both stationary and non-stationary speeds. In this study, phase voltage and AD-OT transformation have been used for the first time for detection the demagnetization fault in PMSM. The presented method does not bring additional cost to the end user since motor driver systems already contain voltage sensors.

Acknowledgements

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