Mehmet AKAR[1], **Mustafa EKER**[2]

Gaziosmanpasa University (1,2)

Demagnetization Fault Diagnosis in Permanent Magnet Synchronous Motors

***Abstract**. Permanent Magnet Synchronous Motors (PMSMs) are widely used in industrial automation systems due to their superiorities such as high efficiency and power factor, high power-weight ratio and high moment-inertia ratio. A new method to determine demagnetization faults in PMSMs has been presented in this study. The motor phase current has been monitored under differing speed and load conditions such as with stationary and non-stationary rotor speed and the demagnetization fault in PMSMs has been detected using Angular Domain Order Tracking (AD-OT) method. The obtained results have been compared with traditional Fast Fourier Transform (FFT) results. In conclusion, it has been observed that the proposed method has been successful in the detection of faults in stationary and non-stationary signals. Even though the proposed method has been used for a long time with vibration signals, it has been applied to PMSM current for the first time and very successful results have been obtained in the detection of demagnetization fault.*

***Streszczenie.** W artykule przedstawiono nową metodę wykrywania demagnetyzacji w maszynie PMSM. W algorytmie wykorzystano metodę AD-OT (ang. Angular Domain-Order Tracking). Wyniki badań metody porównano z działaniem FFT. Proponowany algorytm skutecznie identyfikuje awarię zarówno w stanie ustalonym, jak i dynamicznym. (**Identyfikacji awarii demagnetyzacji w maszynie synchronicznej z magnesami trwałymi**).*

Keywords: Demagnetization, fault diagnosis, permanent magnet synchronous motors.
Słowa kluczowe: demagnetyzacja, wykrycie awarii, maszyna synchroniczna z magnesami trwałymi.

I. Introduction

Permanent Magnet Synchronous Motors (PMSMs) have started to be preferred more for industrial applications that require high performance in comparison with other motors. The reasons for the selection of these motors can be listed as; their ability to operate in various speeds, their higher efficiencies in comparison with asynchronous motors, their small size when compared with the power, volume and weight ratios of other motors, their integrated structure, their ability to adopt formally to construction equipment, their good speed control facilities and their low inertia. [1].

Even though regular periodic maintenances increase the fault period of electric motors as in all rotating machines, they are insufficient to prevent faults. Therefore, predictive maintenance instead of periodic maintenance is one of the most important topics emphasized by maintenance engineers and scientists.

PMSM faults can be classified as electrical faults (drive and winding faults), mechanical faults (bearing faults and eccentricity) and magnetic faults (demagnetization) [2]. Demagnetization faults in PMSMs generally occur due to factors such as load situations that require high starting torques and fixture reaction that occurs during the rapid change from transient situation to stationary state, magnetic fields in opposite directions that are caused by currents passing through stator coils in static state and high temperature that occur during winding faults [3,4]. Irreversible losses occur as a result of fluxes produced by the magnets which in turn cause decrease in motor efficiency [5]. In addition, vibration and increase in noise are observed due to unbalanced magnetic pull caused by the demagnetization fault. Motor current signal analysis (MCSA) is the most commonly used method in fault diagnosis. The method is based on the monitoring of the amplitude changes of the special frequency components related to the fault in the spectrum graph of the monitored current signal [6]. Even though the method gives successful results for stationary signals, it is not successful for non-stationary signals due to the inadequacy of the FFT method. Since PMSMs are operated according to the determined acceleration and deceleration reference speeds, both the amplitude and the frequency of the current drawn in these regions are dynamic. The suggested method resamples the current signal according to the speed signal and shifts the signal which is dynamic in the time domain to stationary state in the angular domain. Therefore, fault diagnosis is easily carried out in this case when FFT is applied to the signal in the angular domain due to the success of FFT for stationary signals.

This paper is divided into six sections. Following the introduction, Section 2 presents and discusses PMSM with demagnetization fault. Section 3 introduces AD-OT and corresponding algorithms to obtain the angular domain representation of a stationary and non-stationary signal. Experimental test rig and data acquisition process are presented in Section 4. Obtained FFT and AD-OT results are presented in Section 5, as well as the feature extraction method by means of order components of the current signal. Finally, conclusions are stated in Section 6.

II. PMSM with Demagnetization Fault

The wide usage areas of PMSMs bring with them the faults that may occur in these machines. One of the faults observed in PMSMs is demagnetization which is a magnetic fault. Demagnetization fault may occur especially in high loads or due to armature reaction that occurs during the rapid change from permanent situation to static state [3]. In addition, demagnetization fault is also caused due to magnetic fields in the opposite direction that occur as a result of currents passing through stator windings in stationary state and high temperatures that occur in winding faults [4]. Demagnetization fault is caused by the additional sideband components of the motor current in the FFT spectrum. The location of these sideband components can easily be calculated using Eq. 1 [7].

$$f_{dm} = f_s\left(1 \mp \frac{k}{p}\right) \tag{1}$$

where f_{dm} is the demagnetization fault frequency, fs is the electrical fundamental frequency, k is an integer and p is the number of pole pairs.

Demagnetization fault has been examined in detail by many researchers in recent years. Rajagopalan et.al. [8] have tried to diagnose demagnetization fault in a motor working under dynamic operating conditions via Winger,Ville distribution. In another study, motor line current and the harmonics of the zero component current were examined in order to diagnose the demagnetization fault in PMSM [9]. When compared the results have shown that motor line current FFT results can be used at nominal and high speeds whereas zero component current FFT results can be used at low speeds to diagnose demagnetization fault. Discrete Wavelet Transform and Hilbert Huang transform have been used in the diagnosis of demagnetization fault in other studies carried out by researchers. Fault diagnosis has been carried out successfully as a result of the methods they applied to the stator current. The results obtained have shown that diagnosis can be made at low, nominal and high motor operating speeds [10,11]. Rajagopalan et.al. [12] have examined the stator current behavior under differing load conditions. Through the simulation and experimental studies carried out, they have shown that motor current can be used successfully in the diagnosis of demagnetization fault [13]. Casadei et.al. [14] have monitored the back emf signal to diagnose magnet fault. They have determined via applications using Finite Elements Method that their suggested method can successfully be used for the diagnosis of demagnetization fault. Another study carried out has examined the demagnetization fault in PMSM operating under dynamic conditions via Hilbert Huang transform and compared the results with the classic FFT method [15]. While it has been observed that the FFT method is insufficient for fault diagnosis under non-stationary speed, they have also observed that their suggested method can successfully be used for demagnetization fault diagnosis. Khoobroo and Fahimi [16] have examined the effect of demagnetization fault on motor electromagnetic torque. They showed that there is a decrease in the average torque and oscillations in the torque signal due to the fault. Espinosa et.al. [17] have suggested a new method for the diagnosis of broken magnet fault in PMSMs working under dynamic operation conditions. The researchers have applied Hilbert Huang transform to motor current to obtain instantaneous frequency components. The simulation and experimental study shows that their developed method effectively diagnoses broken magnet fault. Jongman et.al. [18] have suggested an offline method for the diagnosis of demagnetization and eccentricity fault diagnosis. The researchers have excited the d axis after stopping the motor via dc or ac current after which they have examined the variations that occur as inductance due to the fault. Casadei et.al. [19] have examined the changes in the emf signal of a five phase PMSM via analytical methods and simulations. In another study, demagnetization fault diagnosis has been carried out by examining supply voltage zero component [20].

III. Angular Domain Order Tracking Method

Order tracking (OT) is the frequency component analysis method in rotary machines due to rotor speed. Obtaining correct results from analyses carried out under non-stationary operating conditions depends on the correct measurement of rotor speed [21]. AD-OT method samples the data filtered using analog anti-alias filter in fixed intervals of Δt. The uniformly sampled time data is digitally transformed from the time domain to the angular domain using adaptive digital resampling algorithm [22]. The steps for the transformation from time domain to angular domain are shown in Fig. 1 [22]. As can be seen in Fig. 1, the data for which angular transform has been completed is FFT transformed and the amplitude and phase of the order component are obtained. When the equalities used for the FFT transform in the time domain are revised in the angular domain, Eq. 2 is obtained [22].

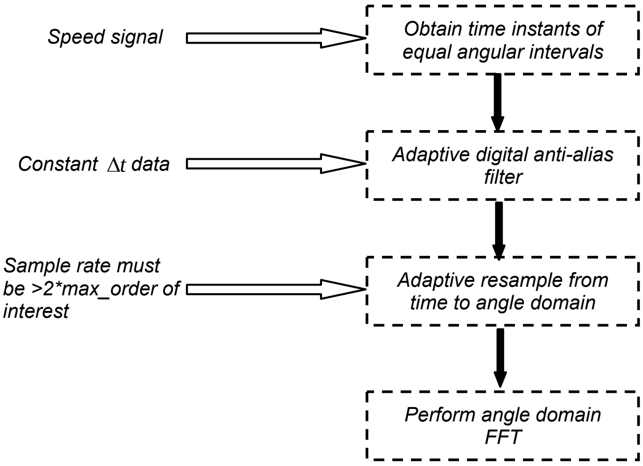


Fig. 1. Flow chart of resampling based order tracking process

$$\Delta_0 = \frac{1}{R} = \frac{1}{N*\Delta\theta}$$

$$O_{nyquist} = O_{\max} = \frac{O_{sample}}{2} \tag{2}$$

$$O_{sample} = \frac{1}{\Delta\theta}$$

where Δ_0 is the order spacing of the resulting order spectrum, R is the total number of revolutions that are analyzed, N is the total number of time points over which the transform is performed, $\Delta\theta$ is the angular spacing of the resampled samples, O_{sample} is the angular sample rate at which the data is sampled, $O_{nyquist}$ is the Nyquist order and $O_{\max}$ is the maximum order that can be analyzed. As can be seen in the Eq. 2, the order resolution depends on the number of rotations of the rotor during transformation. The minimum sampling rate required to prevent aliasing is maximal two samples per cycle as in the time domain data. The kernels of the FFT are reformulated according to the uniform angular intervals [22].

$$a_m = \frac{1}{N}\sum_{n=1}^{N} x(n\Delta\theta)\cos(2\pi o_m n\Delta\theta) \tag{3}$$

$$b_m = \frac{1}{N}\sum_{n=1}^{N} x(n\Delta\theta)\sin(2\pi o_m n\Delta\theta)$$

o_m, a_m and b_m expressions given in Eq. 3 represent respectively the order which is being analyzed, Fourier coefficient of the cosine term for o_m and the Fourier coefficient for the sinus term 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 Eq. 4.

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

where n_r is the rotor speed.

IV. Experimental Study and Data Acquisition

In this section the experimental study is explained. In the experimental study a motor with shaft power of 1.2kW with 8 poles, 230 VAC, a nominal torque of 4 Nm and a nominal speed of 3000 rpm was used. PMSM was used in closed loop speed control mode. A second PMSM with the same properties was operated in closed loop torque control mode and was used as a brake. The experimental setup and equipment can be seen in Fig. 2.

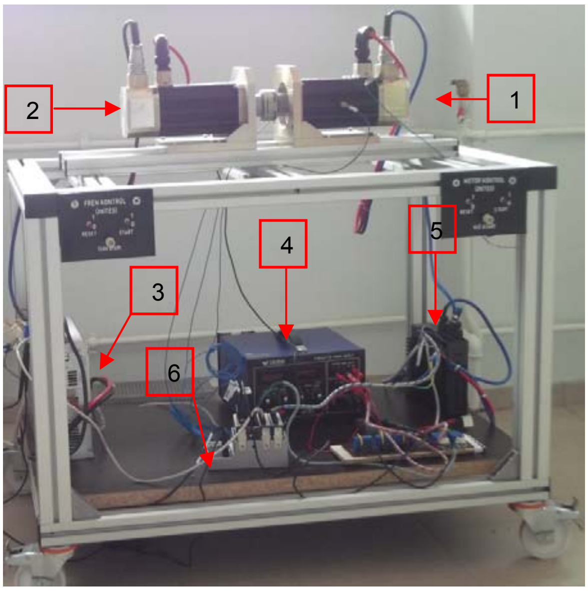


Fig. 2. Experimental test rig (1:PMSM, 2:Brake, 3:Brake controller, 4:Power supply, 5:Motor controller, 6: Data acquisition board)

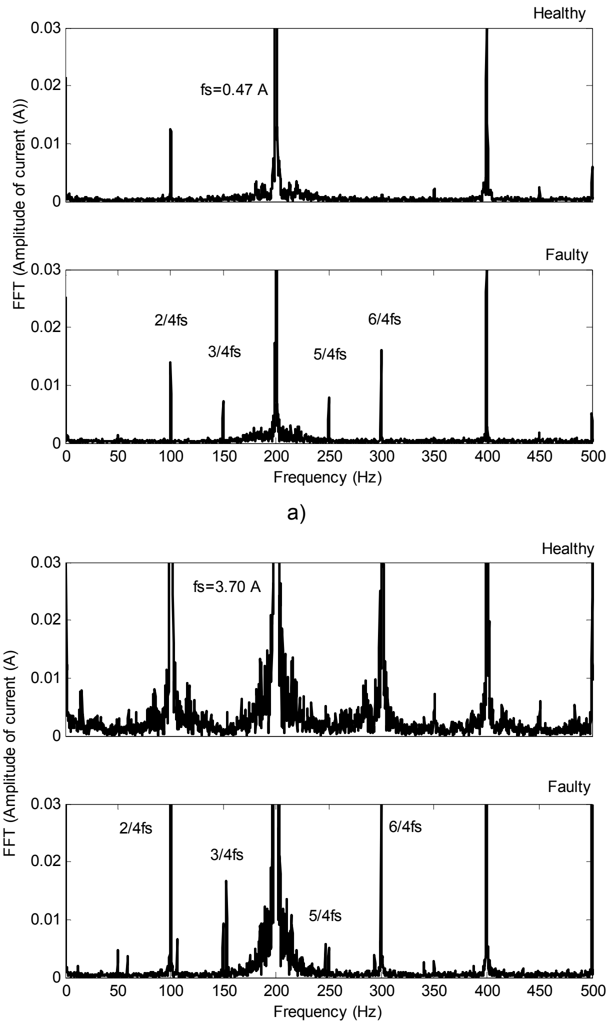
Demagnetization fault was carried out thermally during the manufacturing stage. The operating temperature of the magnets belonging to one pole was raised about 120^0C to create a demagnetization fault of about 50 % in one of the poles. The PMSM used in the experimental studies were operated at speeds of 750 rpm (50 Hz), 1500 rpm (100Hz) and 3000 rpm (200 Hz) and loads of 0%, 25%,..,125% for every speed and current rotor speed has been monitored. Data acquisition has been carried out using CDAQ-9174 module, NI9227 current module and NI9239 voltage module for a period of 10 seconds with a sampling frequency of 25600 Hz. LabVIEW Sound and Vibration Assistant Toolkit 2011 software has been used in data acquisition and evaluation. Afterwards the faulty motor was attached to the test rig and the experimental procedure given above has been repeated.

V. Analysis Result

The signals monitored in the presented study have been analyzed using FFT and AD-OT methods and the obtained results have been compared for stationary and non-stationary speeds.

FFT Results

First, the motor was operated at its nominal speed of 3000 rpm and spectrum values have been examined for the healthy and faulty conditions. When Fig. 3 is examined, sideband components at the 2/4 and 6/4 multiples at the fundamental frequency of the healthy motor under no load and full load current spectrums. These components are misalignment components that occur due to the brake and alignment problems. Whereas additional components at frequencies of 3/4fs and 5/4fs are observed at the current spectrum for demagnetization fault. The current spectrums obtained at operating frequencies of 100 Hz and 50 Hz support the graphical results given in Fig. 3.



a)

b)

Fig. 3. FFT stator current spectrum for a constant speed of 3000rpm (a-No load, b-full load)

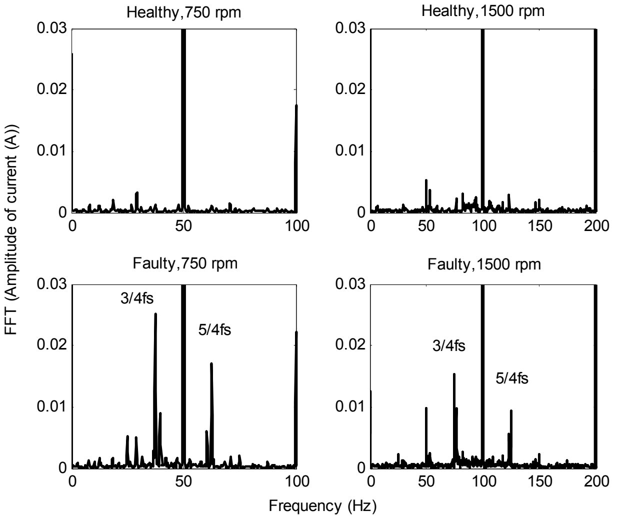


Fig. 4. FFT stator current spectrum for a constant speed at full load

PMSMs are operated under dynamic operating conditions according to the defined acceleration and deceleration reference ramps. Current and speed graph for a PMSM with demagnetization fault operating under dynamic conditions have been given in Fig. 5.

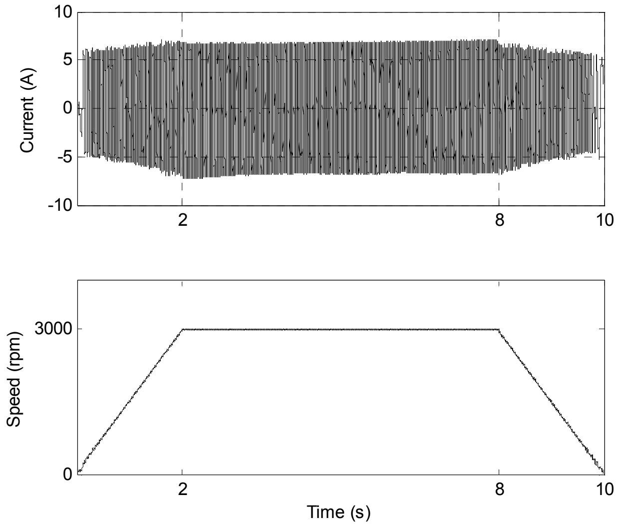


Fig. 5. Motor current and speed signals for a speed change from 0-3000-0 rpm operating at full load.

As can be seen from the figure, both the amplitude and the frequency of the motor current have a dynamic structure in acceleration (0-2s) and deceleration (8-10s) regions. The FFT graphs obtained in this condition have been given below.

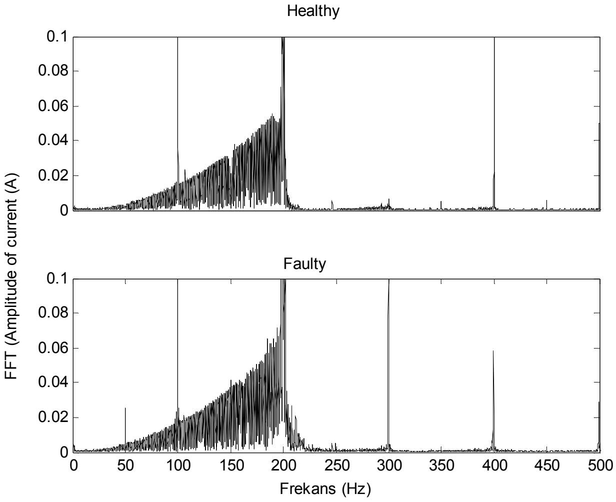


Fig. 6. FFT stator current spectrum for a speed change from 0-3000-0 rpm operating at full load.

The fault components that occur in stationary signals at frequencies of 3/4fs and 5/4 fs are not observed in the non-stationary current signal. Even though the FFT method is successful for stationary signals, they can cause faulty diagnosis due to the fact that they do not contain information regarding the time interval during which changes occur in non-stationary signals.

AD-OT Results

As was explained in the previous section, the FFT method which gives successful results for stationary signals is insufficient for non-stationary signals. The AD-OT method has been presented in this section for the analysis of non-stationary signals. The method is based on the resampling of the non-stationary current signal according to the non-stationary speed signal. Thus, the signal which is dynamic in the time domain becomes stationary in the order domain. Since the disadvantage of the FFT method will no longer be valid, the FFT results of resampled signal will include sufficient information regarding the fault. The spectrum graph obtained as a result of the AD-OT transform of the PMSM operating under the conditions determined for Fig. 5 has been given below.

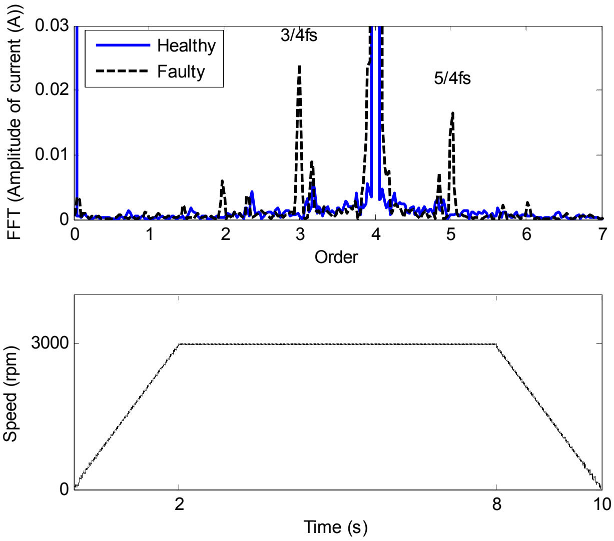


Fig. 7. AD-OT stator current spectrum for a speed change from 0-3000-0 rpm operating at full load.

The location of any frequency component is calculated via Eq. 4 in the order spectrum. Rotor speed changes according to frequency in PMSMs. In this case, the fundamental component will rise up to 4th order level no matter what the load leve and basic operating frequency are. If the components of the fault in the FFT are 3/4fs and 5/4fs, they will be at about 3rd and 5th order levels. Since the method resamples the dynamic current signal according to the speed signal, it contains accurate information at dynamic conditons just like in stationary operation. As can be see in Fig. 7, there is a great amplitude difference between the healthy and faulty cases at 3rd and 5th order levels. The dynamic operating condition has been repeated ensuring that the reference speed will be 0-750-0 rpm, 0-1500-0 rpm whereas the reference load will be 0 %, 25 %, ...,125 %.

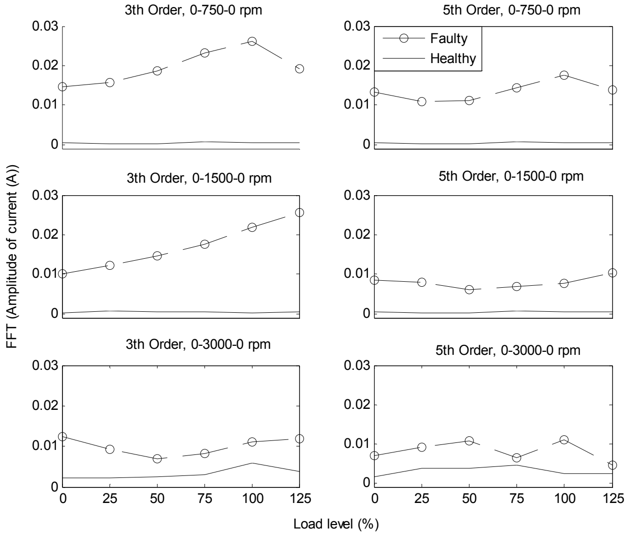


Fig. 8. Amplitude variations of the 3th and 5th orders according to load levels

When the Fig. 8 is examined, it can be seen that the 3rd order component contains more explicit information in comparison to the 5th order component. The amplitude at the 3rd order level under full load for healthy and faulty condition has changed from 0.49 mA to 26.2 mA for 0-750-0 rpm, from 0.21 mA to 21.9 mA for 0-1500-0 rpm and from 5.9 mA to 11.2 mA for 0-3000-0 rpm. As can be seen from the obtained results, there is a decrease in the amplitude values of the components of speed increase and fault. However, the amplitude change in the healthy and faulty case at even the full speed is about %90. This makes it possible to clearly carried out fault diagnosis.

VI. Conclusions

In this study, the effect of demagnetization fault on the PMSM current spectrum has been examined in detail via FFT and AD-OT methods and the obtained results have been compared. When the FFT results are examined, it was observed that they contained explicit information regarding the stationary operating conditions for the motor, however it has also been determined that fault diagnosis is not possible for non-stationary condition. Whereas when the results of the propose method are examined, it has been observed that the fault is clearly diagnosed for both the stationary and non-stationary condition and at various speed and load conditions. In addition, fault diagnosis is easier in the proposed method when the location of the fault component is constant at the 3rd and 5th order values regardless of speed and load levels. Even though the proposed method has been used for many years for vibration signals, it has been applied to PMSM current for the first time in this study and has successfully diagnosed demagnetization fault. The fact that the current and speed sensors required for the use of the proposed method are existed in the motor drive enables online motor monitoring possibility with no additional cost. This will reduce the maintenance costs while increasing the safety of the plant and the productivity.

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Authors:

Dr. Mehmet Akar, Gaziosmanpasa University, Mechatronics Engineering Department, 60150 Tokat, Turkey, mehmet.akar@gop.edu.tr

Mustafa Eker, Gaziosmanpasa University, Mechatronics Engineering Department, 60250 Tokat, Turkey, mustafa.eker@gop.edu.tr