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DIAGNOSIS OF STATIC ECCENTRICITY FAULT IN PERMANENT MAGNET SYNCHRONOUS MOTOR BY ON-LINE MONITORING OF MOTOR CURRENT AND VOLTAGE

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ABSTRACT

This paper presents an experimental study on diagnosis of eccentricity fault in permanent magnet synchronous motor (PMSM). The study carried out by analyzing the harmonics obtained using Power Spectral Density (PSD) of stator current and voltage at no load condition. Motor stator current and voltage are uploaded to pc with software of used inverter and their harmonics obtained by using LabVIEW Signal Express Toolbox program for healthy and faulty condition. In addition, performance of the motor over the period of starting up to the steady state is investigated. The experimental results are illustrated in graph diagrams and results showed that the presented method is very effective and easy to use for prognosis of static eccentricity fault.

Keywords: *Eccentricity, Fault Diagnosis, Power Spectral Density, Permanent Magnet Synchronous Motor.*

INTRODUCTION

Permanent Magnet Synchronous Motor is a rotating electric machine in which the stator is a classic three phase stator like that of an induction motor and the rotor has surface or interior mounted permanent magnets. So the PMSM is equivalent to an induction motor where the air gap magnetic field is produced by a permanent magnet. Recently, PMSM has been used widely because of the high energy-density permanent magnet (PM) materials at

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competitive prices, continuing breakthroughs and reduction in cost. The PMSM has many advantageous compared with dc brush and induction motors. They can be described as follows [1]:

- High dynamic response
- High efficiency providing reduction in machine size
- Long operating life
- Noiseless operation
- High power factor
- High power to weight ratio
- High torque to inertia ratio
- High air-gap flux density
- Higher speed ranges
- Better speed versus torque characteristics
- Lower maintenance cost
- Simplicity and ruggedness
- Compact design
- Linear response
- Controlled torque at zero speed

Thanks to these advantageous the PMSM is the optimal solution for the most field of application as below [2]:

- Packaging
- Textile
- Glass Wood
- Robotics
- Machine tools
- Handling
- Food and Beverage

Electrical machines are break down with time because of passing its life time, selecting wrong rated power, misusing of motor, deficient production and insufficient repairing. These faults can be classified and seen clearly at table1 and figure 1 respectively.

Table 1: Percentage of failures [3]

Faults	IEEE-IAS (%) Electrical Safety Workshop	EPRI (%) Electric Power Research Institute
Bearing	44	41
Winding	26	36
Rotor	8	9
Other	22	14

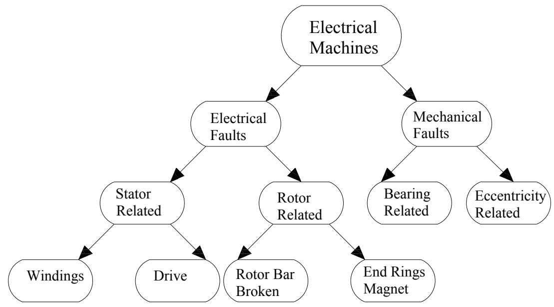


Figure 1: Induction motor fault scheme [3]

Almost 40-50 % of all motor failures are related to mechanical faults [4]. Mechanical faults have caused to a noise and vibrations. Rotor eccentricities and mechanical rotor imbalances can be diagnosis by monitoring electrical quantities (motor current, voltage and instantaneous power) and mechanical quantities (vibrations and torque oscillations) [5]. The failure of PMSM has a serious impact on the operation of a system and it case some results such as lost production, while in others it may jeopardize human safety [6]. So, the condition monitoring of this motors can significantly reduce cost of maintenance by the early detection of faults.

Many diagnostic methods have been improved for prognosis of electrical machines faults by using difference fault-related signals. They can be described as follows [7]:

- Electromagnetic field monitoring
- Temperature measurements;
- Infrared recognition;

- Radio-frequency (RF) emissions monitoring;
- Noise and vibration monitoring;
- Chemical analysis;
- Acoustic noise measurements;
- Motor-current signature analysis (MCSA);
- Model, artificial intelligence, and neural network based techniques.

MCSA is a monitoring technology developed by the Oak Ridge National Laboratory (ORNL) and it is the most popular technique in mentioned techniques. It is now widely used to diagnose problems such as broken rotor bars, abnormal levels of air gap eccentricity, shorted turns in low voltage stator windings and mechanical problems. This method provides a highly sensitive, selective and cost effective means for on-line monitoring of heavy industrial machinery.

2. STATIC ECCENTRICITY FAULT

Eccentricity related fault is the condition of unequal air gap that exist between the stator and rotor. Air gap eccentricity fault can occur due to inaccurate positioning of the rotor with respect to the stator, bearing wear, stator core movement, shaft deflection etc [7]. Two types of eccentricity fault occur in electrical machines. These are dynamic eccentricity (DE) and static eccentricity (SE) faults. These faults are illustrated in figure 2 [8].

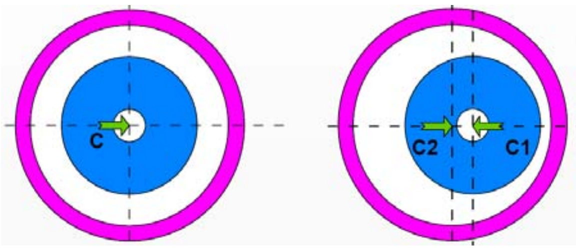


Figure 2. Types of eccentricity faults

C is the center of rotation, C1 is the center of rotor and C2 is the center of stator in figure 2. According to DE; the center of the rotor is not at the center of the rotation (C2 is centre of rotation). For this reason the position of minimum air gap rotates with the rotor. Several factors cause to DE fault such as a bent rotor shaft, bearing wear or misalignment of bearings, mechanical resonance at critical speed, etc [8]. SE fault occurs when the rotor rotates about its own centerline, but this centerline does not coincide with that of the stator bore (C1 is centre of rotation). SE can be caused by oval stator cores or by the incorrect positioning of the stator or rotor [8]. But generally SE and DE exist together and this situation is called mixed eccentricity fault (Rotation position is anywhere between C1 and C2).

Although there are a lot of researches on eccentricity fault in induction motor, there are a few studies on PMSM eccentricity fault. Rosero et al. reported an experimental study for diagnosis of the broken bearings and eccentricity faults [4]. In this study stator current harmonics were obtained using stator current spectrum. In another study they used two dimensional (2D) Finite Element Analysis (FEA) method for the diagnosis of dynamic eccentricity [9].The simulation results were analyzed by means of Continues Wavelet Transform (CWT). Bashir et al. used the amplitude of the harmonic components with a particular frequency pattern is called index [10]. Index was used for noninvasive diagnosis of static eccentricity in PMSM. To evaluate the ability of the proposed index for static eccentricity detection and estimation of its severity, the correlation between index and eccentricity degree is calculated. They used three layer artificial neutral networks to classify the current and torque profiles.

The sideband components occur around the fundamental frequency in PMSM current and voltage while motor is running under the static eccentricity fault. These sideband components are calculated with eq.1 [10].

$$f_{SE} = (1 \mp \frac{2k-1}{p}) f_s$$

(1)

Where f_s is the supply frequency, p is the number of pole pairs and k is an integer.

3. POWER SPECTRAL DENSITY TRANSFORM

A lot of methods have been successfully used for analyzing the time signals in frequency domain such as Fourier Transform (FT), Short Time Fourier Transform (STFT), Fast Fourier transform (FFT) and Power Spectral Density (PSD).

FT, which was firstly used by Joseph Fourier in 1807, defines a relationship between a signal in the time domain and its representation in the frequency domain. According to FT, all of continuous functions, which have fundamental period ($T_0 (w_0 = 2\pi / T_0)$), can be express by the trigonometric functions [11]. Although FT was successfully used stable signals, it was insufficient at the unstable signals because of missing time data. This problem achieved from Denis Gabor by using STFT in 1946. The STFT analyzed the time signal by windowing so STFT is also called the windowed Fourier transform. The STFT use different type of windowing functions such as '*hanning*', '*hamming*', '*chebyshev*' and '*kaiser*' etc. But the STFT applications in engineering are limited because of its fixed window which results in low time frequency resolution.

Recently FFT has been used efficiently for signal processing applications such as motor current signal analysis and digital signal processing. The FFT is another using method for calculating the Discrete Fourier transform. While it produces the same result as the other approaches, it is incredibly more efficient and reducing the computation time. This method operates by decomposing N point time domain signal into N time domain signals each composed of a single point. The second step is to calculate the N frequency spectra corresponding to these N time domain signals. Lastly, the N spectra are synthesized into a single frequency spectrum [12]. The PSD has been the estimation of spectrum of discrete time deterministic and stochastic processes and it has generally used useful signal processing techniques. The PSD processes simply to find the discrete time Fourier transform of the collected signals take the magnitude of results. The PSD refers to the amount of power density of spectral as a function of the frequency. The PSD describes how the power of a time series is distributed with frequency. By knowing the PSD and system bandwidth, the total power can be calculated. The FFT can convert time domain signals $ws_i(n)$ into the frequency domain:

$$ws_i(f) = \frac{1}{M} \sum_{n=0}^{M-1} ws_i(n)\, e^{-j2\pi n \frac{f}{M}}$$

(2)

Where f is discrete frequency, f=0,1,2,…N, the raw power spectral estimate can be formed:

$$PSD_i(f) = ws_i(f) \times ws_i^{*}(f)$$

(3)

Where * denotes the complex conjugate [13]. Also raw PSD estimates from all segments can be averaged to give the following eq. 4:

$$PSD(f) = \frac{1}{k} \sum_{i=0}^{k-1} PSD_i(f) \quad (4)$$

4. APPLICATION

In this study, PMSM was used with parameters as given in table 2. The motor was controlled by using closed loop speed control mode and drived by Pulse Width Modulation (PWM) inverter. The fault detection system which uses only the motor terminal voltage and current as an inputs and motor control flow diagram are shown in Figure 3 [14].

Table 2: PMSM nominal data

Power	0.82 KW
Voltage	U_{1N}=147 V
Pole pairs	p=4
Phases	3
Speed	n_{max} =9000 rpm, n_n =3000 rpm
Torque	M_0 =3 Nm, M_n =2.6 Nm
Current	I_0 =3.9 A, I_n =3.5 A

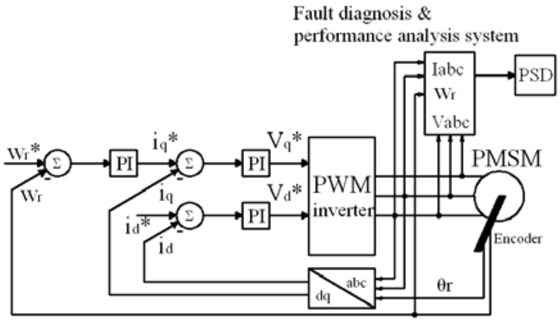
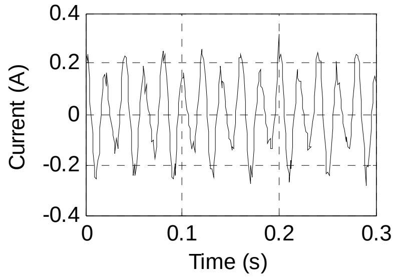


Figure 3. Fault detection system and motor control flow diagram

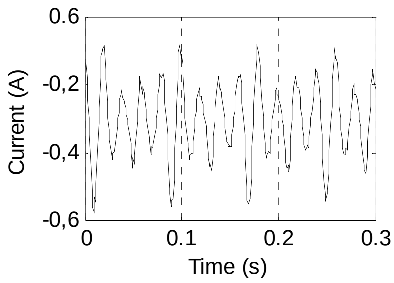
The purpose of motor monitoring system is to measure motor stator current and terminal voltage. The measured current and voltage signals were uploaded to pc with software of used inverter and then signals harmonics were obtained by using LabVIEW Signal Express toolbox. Motor current and voltage data were collected at 2 kHz sampling rate at no load condition for healthy and faulty condition. Motor test bench is shown in Figure 4.

Figure 4. Motor test bench

Firstly the motor was worked at 750 rpm (f=50 Hz) at no load condition and motor current, voltage, rotor speed and electromagnetic torque signals were acquisitioned over the period of starting up to the 60 seconds. Then SE fault carried out with horizontal (angular) misalignment. The angular misalignment was created by PMSM in horizontal plane at rotated specific angle from the original position. Then data acquisition process was repeated for motor under SE fault. Motor time domain current and voltage signals are illustrated for 0.3 seconds in Figure 5 (a), 5(b) and Figure 6 (a), 6(b) respectively.



(a)



(b)

Figure 5. Time domain current signals of PMSM: (a) healthy motor, (b) faulty motor

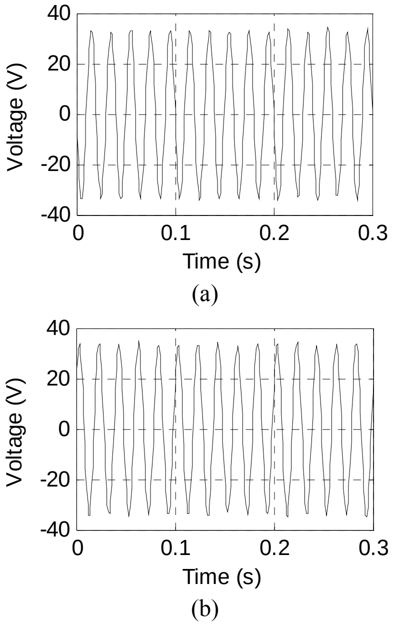


Figure 6. Time domain voltage signals of PMSM: (a) healthy motor, (b) faulty motor

Figure 5 and 6 show that SE fault causes unbalance in stator current and voltage. Especially, unbalance amplitude of current is bigger than the healthy situation. Also time domain signals indicate that it is difficult to diagnosis of SE fault in this domain. It has also known that SE fault disturb to magnetic flux between stator and rotor. This distribution produces harmonics at the motor current and voltage, are calculated by eq.1. To define SE characteristic harmonics, PSD transform was applied to time domain signals with LabVIEW Signal Express toolbox. While PSD was applying Welch method and Hanning window were used with 4096 points. The experimental results showed that there were no extra sideband at the voltage and current spectrum when the motor was healthy. With the SE fault, lower and upper sideband components occurred around both fundamental frequency and its harmonics. The sideband components position depends on the value of p used in eq.1. Current and voltage spectrums are illustrated in Figure 7 and 8 for healthy and faulty situation under no load condition. In figure 7, it is shown that the amplitudes of sideband components in the stator current spectrum are increased from -25.96 dB to -5.33 at 12.5 Hz (-fse2), from -26 dB to 10.95 dB at 37.5 Hz (-fse1), from -26.28 dB to 10.28 dB at 62.5 Hz (+fse1) and from -24.81 dB to -12.38 dB at 87.5 Hz (+fse2). It is also shown in figure 8 that the amplitudes of sideband components in the voltage spectrum are increased from -7.63 dB to -17.03 dB at 12.5 Hz (-fse2), from 6 dB to 29.79 dB at 37.5 Hz (-fse1), from 3.38 dB to 21.54 dB at 62.5 Hz (+fse1) and from -3.54 dB to 10.48 dB at 87.5 Hz (+fse2). In addition of these, the change of the amplitudes of sideband components can also be seen clearly from current and voltage surfaces in figure 9 and 10, respectively.

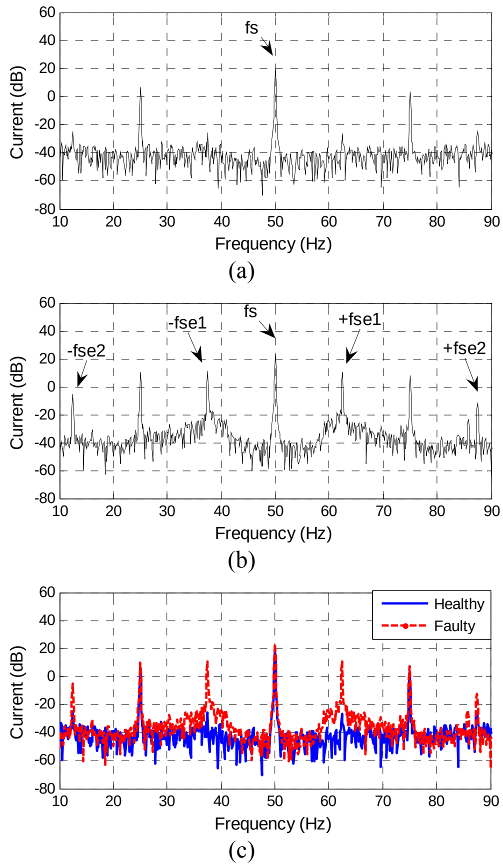
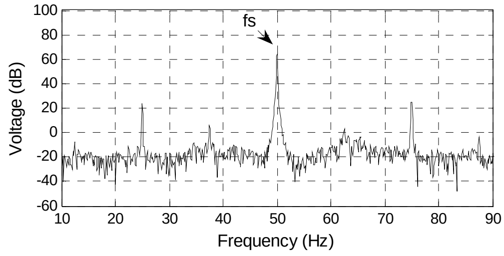
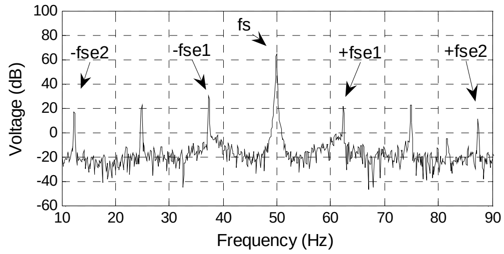


Figure 7.Current spectrums of PMSM: (a) healthy motor, (b) faulty motor, (c) comparative



(a)



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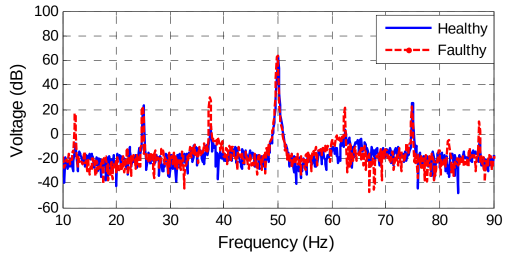
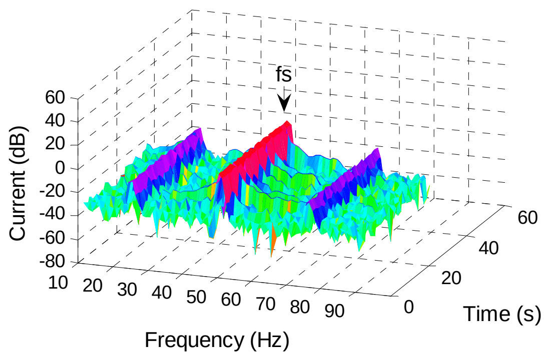
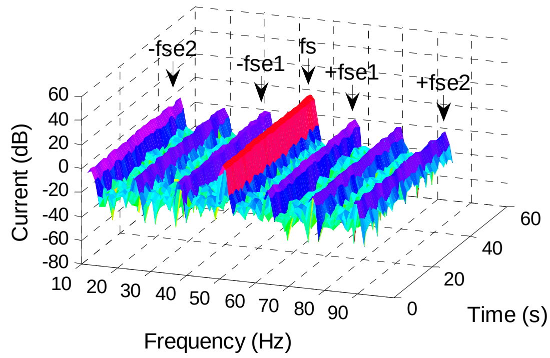


(c)

Figure 8.Voltage spectrums of PMSM: (a) healthy motor, (b) faulty motor, (c) comparative

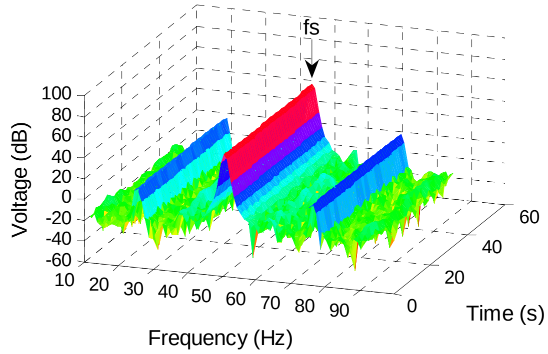


(a)

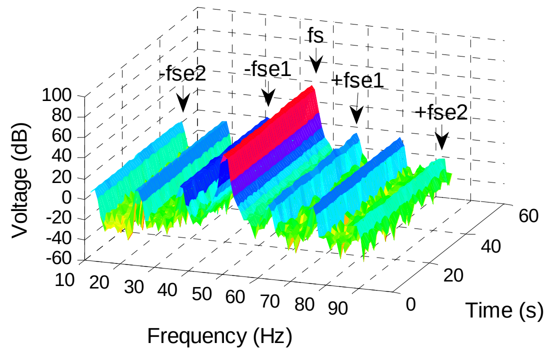


(b)

Figure 9.Current surfaces of PMSM: (a) healthy motor, (b) faulty motor



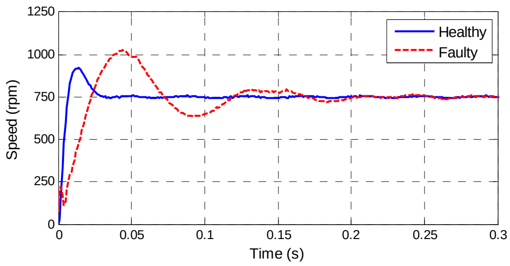
(a)



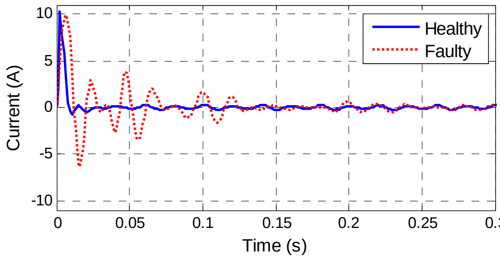
(b)

Figure 10.Voltage surfaces of PMSM: (a) healthy motor, (b) faulty motor

PMSM performance in healty and faulty situations was tested at no load condition over the period of starting up to the steady-state by monitoring motor voltage, speed, and electromagnetic torque are shown in figure 11. The experimental results showed that the overshoot at motor speed is %22 (reference speed 750 rpm) and settling time is 0.075 second in a healthy motor. These values were increased to %36.8 and 0.23 second respectively and oscillation was occurred at the motor transient current and voltage while motor is under SE fault. Motor electromagnetic torque increased and had oscillation due to motor current oscillation.



(a)



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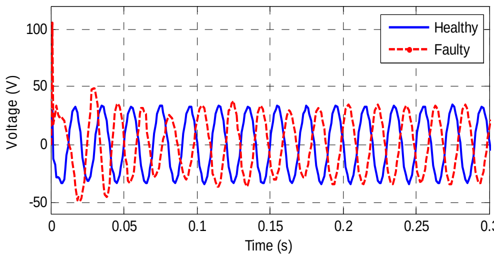

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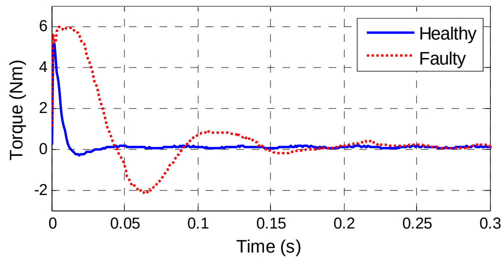

(d)

Figure 11.PMSM performance curves: (a) speed, (b) current, (b) voltage, (d) electromagnetic torque

5. CONCLUSIONS

This study focused on the diagnosis of SE fault on PMSM by on-line monitoring of motor electrical quantities. In time domain, it is difficult to determine effect of fault on the current and voltages signals. So PSD transform was used for defining the characteristic harmonics.

Experimental results showed that SE fault injects harmonics in PMSM current. It is very easy to detect this fault using sideband components harmonics because of these sideband components amplitudes are very small under healthy condition. Especially $\mp f_{SE}1$ components amplitude increase from -26 dB to 10.95 dB at 37.5 Hz (-fse1), and from -26.28 dB to 10.28 dB at 62.5 Hz (+fse1).

In addition, motor terminal voltage was monitored because of not pure sinusoidal structure onto stator voltage. It was seen that there were sideband components in the voltage spectrum and their place were related to p .

Also the experimental results indicate that motor current and electromagnetic torque were increased and they have oscillation over the

period of starting up to the steady-state compared with healthy motor.
Also the speed of the motor has oscillation and its settling time is longer than the healthy motor.

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