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Bearing faults diagnostic in permanent magnets synchronous motor

Diagnóstico de falhas em rolamentos em motor síncrono de ímãs permanentes

Diagnóstico de fallas en rodamientos en motor síncrono de imanes permanentes

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ABSTRACT
With the widespread use of MSAPs in fields such as robotics, automotive, aerospace, medical equipment, renewable energy, etc., the preventive diagnosis of faults affecting these types of motors has become essential to avoid unplanned shutdowns that could lead to considerable financial losses. Even though the permanent magnet synchronous motor is well known for its robustness and efficiency, however it suffers from electrical or mechanical faults. Spectral analysis has become a very important tool for the detection of these faults and we will use this method to determine the frequencies characterizing the fault in MSAPs. It is important to note that the exact distribution of failures can vary depending on the

specific motor and its operating conditions. The characteristic frequencies of the bearing failure are a function of the geometric parameters of the bearing and the motor rotation frequency. Unlike the induction motor, the rotation frequency of the PMSM is fixe, which makes it easier to locate the characteristic frequencies of the bearing fault. This work presents the application of spectral analysis for the diagnosis of the bearing defect and more specifically, that of the outer ring. The experimental results obtained show the interest and effectiveness of spectral analysis for the detection of bearing defects.

Keywords: PMSM. Bearing Fault. Stator Current. Diagnostic. FFT. MLA.

RESUMO

Com a utilização generalizada de MSAPs em áreas como robótica, automóvel, aeroespacial, equipamentos médicos, energias renováveis, etc., o diagnóstico preventivo de falhas que afetam este tipo de motores tornou-se essencial para evitar paragens não planeadas que poderiam levar a perdas financeiras consideráveis. Embora o motor síncrono de ímã permanente seja conhecido por sua robustez e eficiência, ele sofre de falhas elétricas ou mecânicas. A análise espectral tornou-se uma ferramenta muito importante para a detecção destas falhas e utilizaremos este método para determinar as frequências que caracterizam a falha em MSAPs. É importante observar que a distribuição exata das falhas pode variar dependendo do motor específico e de suas condições de operação. As frequências características de falha do rolamento são função dos parâmetros geométricos do rolamento e da frequência de rotação do motor. Diferentemente do motor de indução, a frequência de rotação do PMSM é fixa, o que facilita a localização das frequências características da falha no rolamento. Este trabalho apresenta a aplicação da análise espectral para o diagnóstico do defeito do rolamento e mais especificamente do anel externo. Os resultados experimentais obtidos mostram o interesse e a eficácia da análise espectral para a detecção de defeitos em rolamentos.

Palavras-chave: PMSM. Falha nos Rolamentos. corrente do Estator. Diagnóstico. FFT. MLA.

RESUMEN

Con el uso generalizado de los MSAP en campos como la robótica, la automoción, la aeroespacial, los equipos médicos, las energías renovables, etc., el diagnóstico preventivo de los fallos que afectan a este tipo de motores se ha vuelto fundamental para evitar paradas no planificadas que podrían provocar pérdidas económicas considerables. Aunque el motor síncrono de imanes permanentes es bien conocido por su robustez y eficiencia, sufre fallas eléctricas o mecánicas. El análisis espectral se ha convertido en una herramienta muy importante para la detección de estas fallas y utilizaremos este método para determinar las frecuencias que caracterizan la falla en MSAP. Es importante tener en cuenta que la distribución exacta de fallas puede variar según el motor específico y sus condiciones de funcionamiento. Las frecuencias características de falla del rodamiento son función de los parámetros geométricos del rodamiento y de la frecuencia de rotación del motor. A diferencia del motor de inducción, la frecuencia de rotación del PMSM es fija, lo que facilita la localización de las frecuencias características de la falla del rodamiento. Este trabajo presenta la aplicación del análisis espectral para el diagnóstico del defecto del rodamiento y más concretamente del aro exterior. Los resultados experimentales obtenidos muestran el interés y eficacia del análisis espectral para la detección de defectos en rodamientos.

Palabras clave: PMSM. Fallo de Rodamiento. Corriente del Estator. Diagnóstico. FFT. MLA.

1 INTRODUCTION

The main industrial application areas, related to electric traction, processing, machining, material shaping and recently electric propulsion are increasingly implementing the PMSM. These have a more compact structure, a high mass power, and higher dynamic response compared to conventional structures [6], [7], [9], [18], [20].

These electric machines have to work under different circumstances such as extreme ambient temperature, frequently varying load conditions, fluctuations in voltages and currents, high moisture, and overloads causing faults and failures. Bearing faults are considered the most frequent types and are accountable for 30% to 40% of failures in rotating electric machines. It should be noted that, most of the bearing faults would affect directly the bearing geometrical shape by either rolling elements surface corrugations, inner and outer rings cracks or cage damage. This last fault is found to be the most common in bearing faults. [5], [11], [13], [17].

For this reason, early detection of this type of fault is essential as incipient fault can cause damage that is more serious. This detection will preserve the safety of goods and people and avoid the unscheduled stop of the production line, thus increasing the life of these engines and minimising financial losses. The development of modern diagnosis methods has widely increased due to advances in microelectronics and signal processing. Vibration analysis is a widely used technique for diagnosing bearing faults in rotating machinery. By monitoring and analyzing the vibrations produced by rotating equipment, it's possible to detect abnormalities associated with bearing defects. [3] [4], [10], [15], [16].

In the past few years, various diagnostic methods have been developed to detect bearing faults, depending on the physical quantities chosen. Among these techniques, spectral analysis of the stator current is a very promising approach. Its main advantages lie in the instrumentation used, the ease of implementation and the wealth of information provided on the existence or not of the fault and its severity. [1], [2], [8], [12], [19].

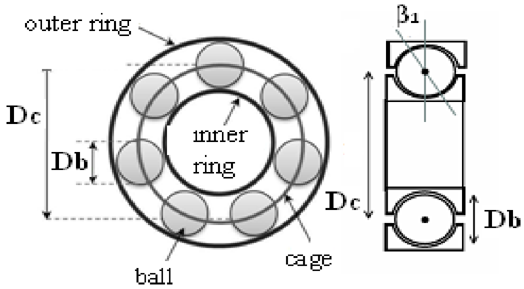
A bearing fault is manifested by the generation of harmonics in the stator current spectrum. These frequencies depend on the both bearing's geometric parameters and the rotation frequency. In induction motors, the rotation frequency varies with the load variation, so the characteristic frequencies of the bearing fault also vary. This problem does not arise in synchronous motors because the rotation frequency is fixed as long as the supply frequency remains fixed.

The present work presents the diagnosis of bearing in permanent magnet synchronous motors by analyzing the spectral characteristics of the stator current. It introduces an enhancement developed in our laboratory, namely the Algorithm for Locating Maxima (MLA) [14]. This algorithm facilitates a clear interpretation of the spectral data, highlighting only the harmonics relevant to bearing faults. Validation of this approach is conducted through experimental tests on a permanent magnet synchronous motor.

2 BEARING FAULTS

Generally, bearings can be categorized as two types, sliding bearings and rolling bearings. Sliding bearings includes linear bearings and journal bearings. Ball and roller bearings, together called olling bearings. Compared with other types of bearings, rolling bearings have many advantages. They are often referred to as antifriction bearings because they require a small amount of lubrication. They are composed mainly of the outer ring, the inner ring, the balls and the cage providing equidistance between the balls. Fig. 1 shows the geometry of the bearing radial ball.

Figure 1. Geometry of the ball bearing



Source: Schoen (1995)

The failure distribution of a permanent magnet synchronous motor (PMSM) can vary depending on various factors such as the motor design, operating conditions, maintenance practices, and environmental factors. However, here are some common types of failures and their distribution in PMSM motors:

Bearing failures are still a common type of failure in PMSM motors, similar to asynchronous motors. The distribution of bearing failures can vary, but generally, outer race failures are more common than inner race or rolling element failures.

There are several types of bearing faults in electrical motors, including lubrication problems, corrosion, fatigue, and wear. Here are some statistics related to bearing faults in electrical motors:

Bearing failures account for around 40-50% of motor failures.

The most common cause of bearing failure is improper lubrication, which accounts for over 60% of failures.

Inadequate or excessive lubrication leads to approximately 80% of premature bearing failures.

Over 50% of all bearing, failures are caused by the ingress of contamination into the bearing system.

Approximately 10-15% of bearing failures are caused by electrical erosion, a phenomenon that occurs due to the passage of electrical current through the bearing.

The estimated cost of bearing failure in the United States alone is approximately $1 billion per year.

The characteristic frequencies of the bearing faults are obtained experimentally using vibration monitoring and analysis. They are based both on the geometry of the bearing and the rotation frequency.

The harmonic frequencies of the different faults in a bearing are given by [14]:

- Outer ring fault:

$$f_{ring,out} = \frac{N_b}{2} f_r(1 - \frac{D_b}{D_c} cos\beta \qquad (1)$$

- Inner ring fault:

$$f_{ring,int} = \frac{N_b}{2} f_r (1 + \frac{D_b}{D_c} cos\beta) \qquad (2)$$

- Cage fault:

$$f_{cage} = \frac{1}{2} f_r (1 - \frac{D_b}{D_c} cos\beta) \qquad (3)$$

- Balls bearing fault:

$$f_{balls} = \frac{D_b}{D_c} f_r (1 - \frac{{D_b}^2}{{D_c}^2} cos^2\beta) \qquad (4)$$

Schoen and co-authors [14] have shown that the bearing faults can manifest themselves as faults in the asymmetric rotor. These are generally classified as harmonics characterizing the eccentricity faults on rotation, which leads to periodic changes of inductances in the machine.

The presence of the bearing fault allows the generation of harmonics in the current spectrum at frequencies [14]:

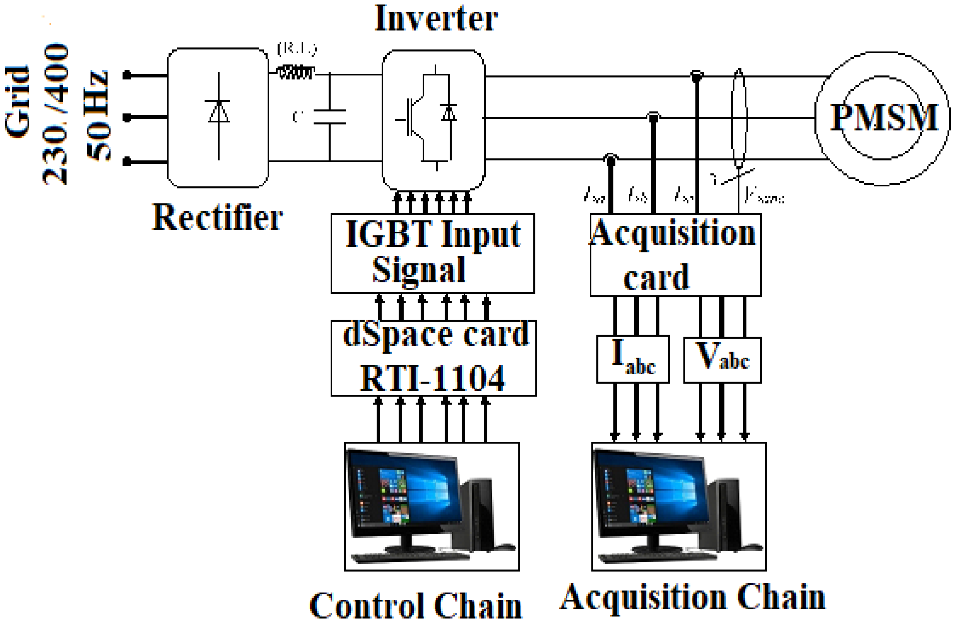
$$f_{bearing} = \left| f_s \mp K . f_{ring,out} \right| \qquad (5)$$

3 EXPERIMENTAL RESULTAS

3.1 DESCRIPTION OF THE MEASUREMENT BENCHS.

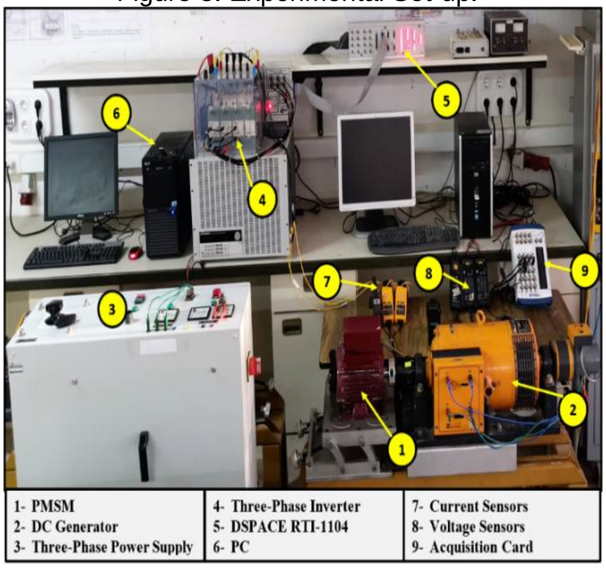
A schematic diagram of the test rig is shown in Figure 2. Figure 3 shows a photo of experimental Set-up in the electric drive development laboratory:

Figure 2. Synoptic diagram of the measurement bench



Source: Authors

Figure 3. Experimental Set-up.



Source: Authors

3.2 CREATING OF THE BEARING FAULTS

The ball bearing diagnosed in this work is the 6204-ZZ type (fan side). Its geometrical parameters are grouped in Table 1.

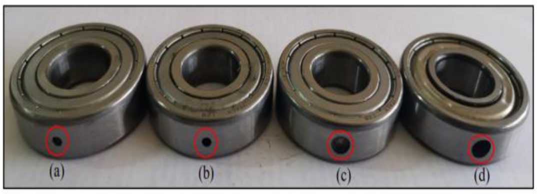
Table 1: Geometric parameters of 6204-ZZ ball bearing.

Parameters	Values
Outer ring diameter	47.00 mm
Diameter of the inner ring	20.00 mm
Cage diameter	33.50 mm
Ball diameter	7.938 mm
Number of balls	8 balls
The contact angle	0

Source: Authors.

The bearing defects treated are those of the outer ring, since it represents 39% of bearing defects according to some statistical studies. They are created artificially by Electrical Discharge Machining, in order to have the same situations as the real defects. The different severities of the outer ring defect achieved are illustrated in the following figure:

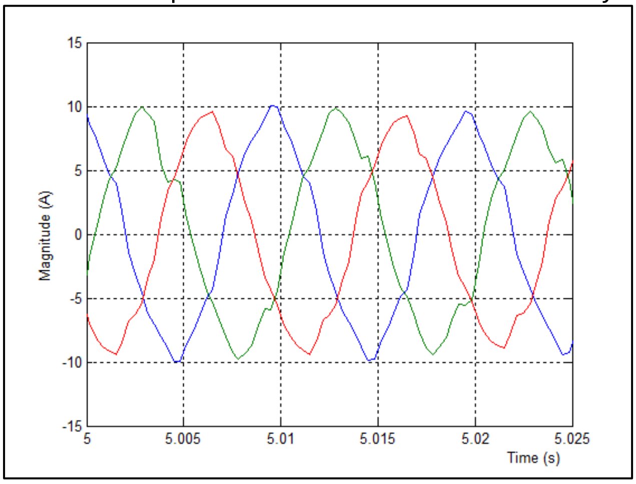
Figure 4. Faults in the outer ring of the bearing



Source: Authors

Theoretically, the bearing outer ring fault manifests itself by creating particular frequency signatures in the stator current spectrum. These signatures are calculated according to equations (1). The bearing outer ring fault is a function of the supply frequency and the rotation frequency. In the case of our machine all parameters are fixed, leading to the frequency 52.6 Hz.

Figure 5. Time shape of the stator current for the healthy case



Source: Authors

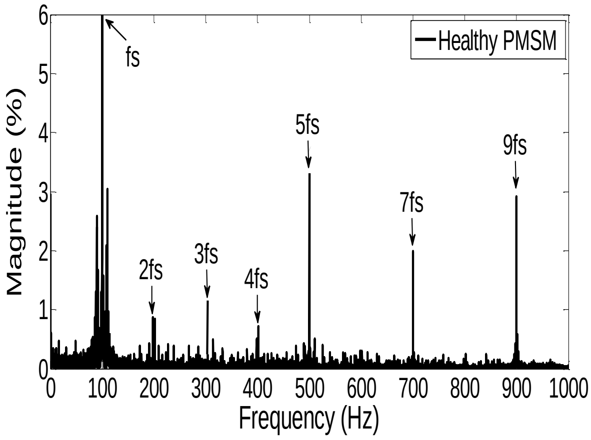
3.3 HEALTHY OPERATION MODE

In order to identify the possible presence of a fault in PMSM using the stator current spectral analysis technique, it is necessary to identify the reference spectrum by analysing the stator current in the case of a healthy motor. Indeed, a comparison of the amplitude of the characteristic harmonic of the fault with that of the reference is often used to detect the presence or absence of a fault and even for monitoring the severity of the fault if it exists.

Figure 5 shows the waveforms of the three stator currents (isa, isb and isc) absorbed by the motor for a healthy operation and under a nominal load. We can see that these currents are balanced but no longer sinusoidal, they show fluctuations, which are due to the coexistence of several harmonics.

In this case, the stator current signal is analyzed assuming that the motor has no apparent fault. Figure. 7, illustrates the stator current spectrum when a two-level inverter supplies the PMSM with a supply frequency of 100 Hz.

Figure 6. PMSM stator current spectrum under the nominal load (19 Nm) for the healthy case

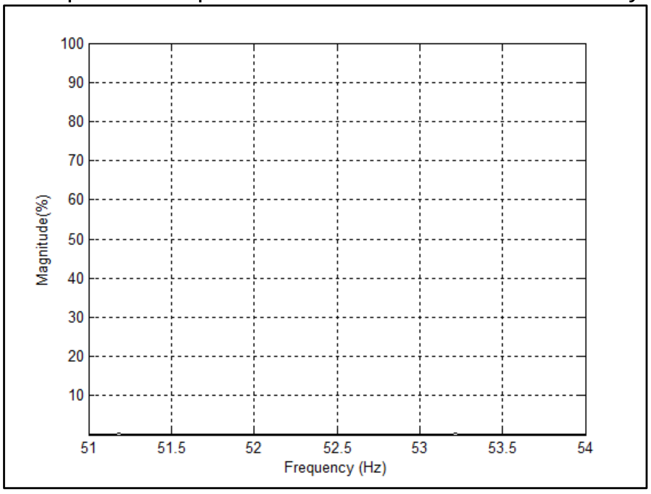


Source: Authors.

From this figure, and due to the switching of the IGBTs in the inverter, we notice that the spectrum of the stator current is highly noisy, which makes it difficult to pronounce with certainty on the existence or absence of one of the defects. To solve this problem, and in order to improve the readability of the spectrum as shown in Figure 7, we used a simple algorithm known as the Algorithm for Locating Maxima (MLA). [02] This algorithm allows the numerical location of the maximum amplitude corresponding to the characteristic harmonic of the fault on the selected analysis band.

According to Table 2, the signatures of the studied faults are located around the fundamental frequency. Therefore, for a better readability of the spectrum, the spectral analysis will be performed only on the frequency band [51Hz – 54Hz] as shown in Figure 7. As this is a healthy operating case, we find that there is no harmonic related to the outer ring fault in this band.

Figure 7. Spectral shape of the stator current for the healthy case



Source: Authors

3.4 MOTOR OPERATION IN THE PRESENCE OF THE BEARING OUTER-RING FAULT

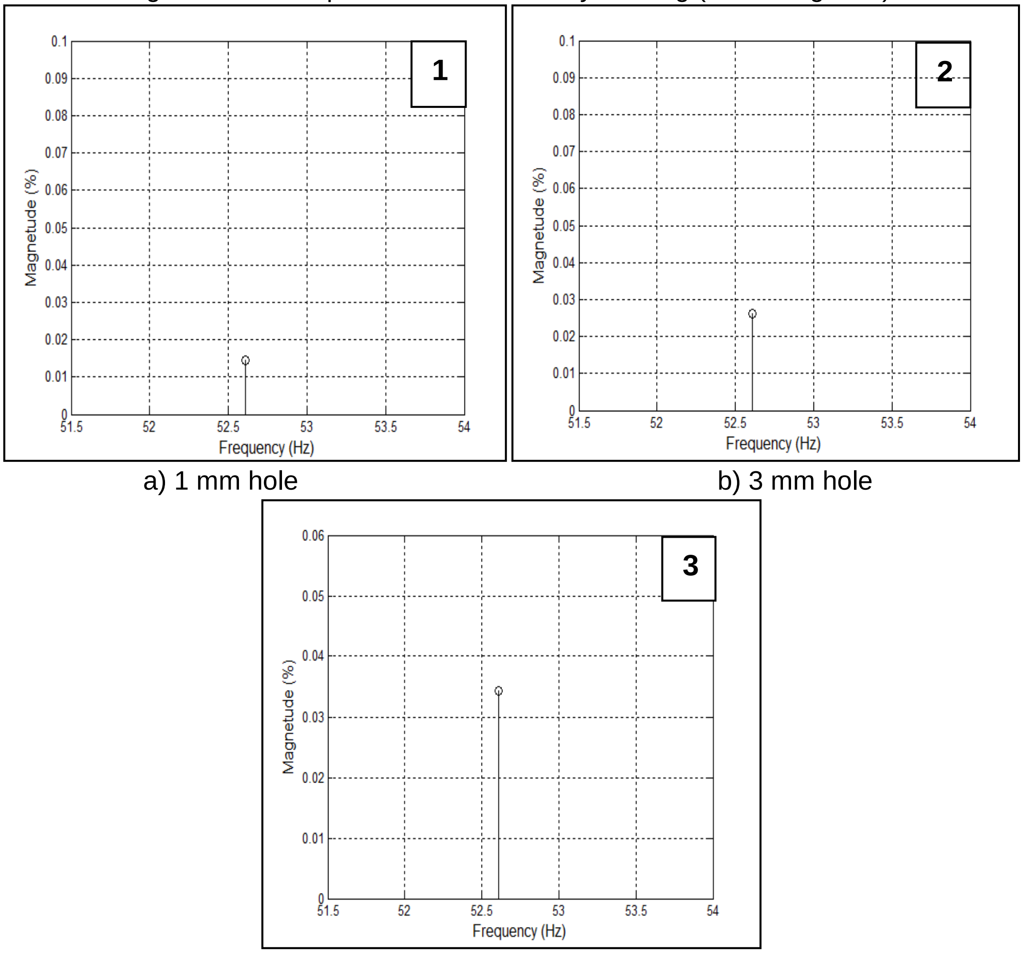
Figure 7 shows the spectra of the stator currents of phase "a", obtained by the estimation of the classical PSD associated with the ALM algorithm for the following operating modes:

Motor operation with a healthy bearing (Figure 8);

- Outer ring fault : 1 mm hole (Figure 8.a);
- Outer ring fault: 3 mm hole (Figure. 8.b);
- Outer ring fault: 6 mm hole (Figure. 8.c);

From these figures, it can be seen that the signature of the outer ring defect appears clearly at the frequency 52.6 Hz, which shows the impact of the MLA algorithm on the readability of the spectrum. It can also be seen that the amplitude of this harmonic increases as the severity of the outer ring defect in the bearing increase.

Figure 8. Motor operation with a healthy bearing (Outer ring fault).



a) 1 mm hole

b) 3 mm hole

c) 6 mm hole

Source: Authors

4 APPENDIX

The PMSM parameters are given by Table 2

Table 2: PMSM Parameters.

Rated power	3 kw
Supply frequency	100 Hz
Rated voltage	360 V
Rated current	5.9 A
Rated speed	1500 rpm
Number of pole pairs	4

Source: Authors

5 CONCLUSION

Diagnosing bearing issues in permanent magnet synchronous motors (PMSMs) is of utmost importance, ensuring optimal operation and prolonging the motor's lifespan. Neglecting such faults can lead to reduced efficiency, increased vibrations, and potential motor failure. The diagnosis of bearing faults through vibration spectral analysis is widely used in the industrial world. However, this technique requires the installation of sensors on the machine, which complicates its use.

Among various diagnostic techniques, spectral analysis of the stator current stands as the most widely used method in fault diagnosis. Fault characteristic harmonics are typically related to the rotational frequency, which remains fixed for a synchronous machine. Consequently, the harmonic frequencies of bearing faults are confined to a specific frequency band, facilitating their detection. In addition, limiting the search interval using the MLA algorithm makes it easier to locate the harmonics characteristic of the fault. Experimental results underscore the effectiveness and utility of this technique in bearing fault diagnosis.

The results obtained also demonstrate that this approach is promising and that its implementation in the industry could improve the diagnosis of bearing faults. However, the low signal level limits their detection. Therefore, it is crucial for researchers to develop signal processing techniques to amplify the signal and identify the characteristic harmonics of the faults.

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