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Research on Mechanical Defect Detection and Diagnosis Method for GIS Equipment Based on Vibration Signal [†]

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Abstract: Gas insulated switchgear equipment (GIS) is widely used in power system, and more attention has been paid to discharge defects than mechanical defects. However, since mechanical defects are a major cause of the failure in GIS, it is of great significance to carry out relevant research on mechanical defects. Detection and diagnosis methods of mechanical defects based on vibration signal are studied in this paper. Firstly, vibration mechanisms of GIS are analyzed. Due to structural differences between single phase insulated type GIS and three phase insulated type GIS, there are big differences in vibration mechanisms between the two types of GISs. Secondly, experimental research on mechanical defects is carried out based on a 110 kV GIS equipment and a self-developed vibration detection system; results show that mechanical defects can be diagnosed by analyzing signal amplitude, frequency spectrum and waveform distortion rate, and a large current is more beneficial for diagnosing mechanical defects. Lastly, field application has been carried out on 220 kV GIS equipment, and a poor contact defect is found, demonstrating that abnormal diagnosis can be realized by method proposed in this paper. Experimental research and field application demonstrate the feasibility and effectiveness of detection and diagnosis method for mechanical defects based on vibration signal and provide experience for subsequent engineering application.

Keywords: gas insulated switchgear; mechanical defect; vibration; detection and diagnosis

1. Introduction

Gas insulated switchgear (GIS) contains many components, including circuit breaker, isolating switch, CT, PT and busbar. In recent years, as the power grid develops rapidly, increased GIS equipment has been widely used due to many advantages, including compact structure, less occupied space, reliable operation and less maintenance work [1]. It is necessary to discover the hidden danger and potential defects of GIS equipment in a timely and effective manner.

Although the failure rate of GIS is relatively low, it is hard to ignore the fault of GIS with extensive use of GIS equipment. Statistics show that GIS defects mainly include partial discharge (PD) fault, mechanical fault and overheating fault; the mechanical fault of GIS occupy the largest proportion. Mechanical fault includes loose contact of the conductor, loose shield and loose bolts, which may cause abnormal vibration [2]. The continuous abnormal vibration may result in SF6 leakage and result in insulation decrease in GIS. Abnormal vibration may also cause PD fault and even breakdown event t. There are many research studies on detection and diagnosis of GIS, including UHF method [3], ultrasonic method [4], chemical method [5] and infrared temperature measurement method. While they are mainly used for studying PD faults and overheating faults, there is relatively little



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). research work of mechanical faults [6,7]. Thus, it is important to study monitoring and diagnosis technology for mechanical faults.

With the advantage of high sensitivity, non-intrusive and anti-electromagnetic interference, a vibration test is a good detection and diagnosis method for the mechanical faults of power equipment, and it has been widely applied on circuit breaker [8], transformers and high voltage reactor [9]. In recent years, vibration test for GIS mechanical faults detection has been studied and applied. Evaluation method on contact faults by measuring vibration signals on the enclosures of GIS is reported in literature [10], demonstrating the feasibility of this method. Under the action of alternating electric field force in GIS, the vibration signal caused by mechanical fault is different from that of the normal situation. In order to detect and diagnose mechanical fault in GIS, it is important to study the vibration characteristics of GIS in depth. Vibration signals of a bus are studied, and the ratio between 1400 Hz component and 100 Hz component is used as characteristic quantity for loose defect in literature [11]. Time domain characteristics and power spectrum are used to analyze vibration signals. It was found that 200 Hz component of GIS equipment with abnormal noise is very big in literature [12]. The influence of air pressure, electrode shape and electric field intensity on vibration spectrum of GIS equipment is studied. However, the research mainly focuses on PD fault and not about mechanical fault in the literature [13]. Time domain and frequency domain features of vibration signals of the switch contact under different contact state are studied in literature [14], it is found that there are obvious 300 Hz and 600 Hz components when the contact condition is poor. The empirical mode decomposition is used for analyzing nonlinear and nonstationary time series in the literature [15]. It provides a reference for the GIS vibration signal. A new algorithm based on the neighbor algorithm and FCM algorithm was adopted to evaluate mechanical condition of GIS in the literature [16]; the key is to calculate cluster centers. A correlation function is adopted to extract characteristic quantity, and a multilayer classifier was adopted to evaluate condition in the literature [17]; however, intelligent detection technology is based on massive data, and a lot of research is needed to enrich the expert database. In summary, it can be observed that the above documents have made significant contributions to the detection and diagnosis technology on mechanical fault in GIS. However, due to the complex structure of GIS and the complicated excitation and transmission of vibration signals in GIS, it is difficult to obtain a general diagnostic process, including characteristic quantity selection and extraction and fault identification. Most of the research studies are carried out in laboratory, and there is less field application. It is necessary to study vibration detection and diagnosis technology for GIS in depth, and carry out field application.

In this paper, research on detection and diagnosis method of mechanical defects based on vibration signal is studied. Section 2 analyzes the characteristics of circulating current and vibration mechanism of GIS and analyzes the vibration character of single phase insulated type GIS and three phase insulated type GIS. Section 3 introduces experimental research on mechanical defects, including GIS platform, detection system, detailed experiments and vibration signal analysis. Section 4 presents field application on 220 kV GIS equipment. Lastly, the full paper is summarized in Section 5.

2. Vibration Mechanism of GIS Equipment

Alternating electrodynamic forces caused by AC current and magnetostriction effect in core coil equipment, such as a voltage transformer, are main reasons for the mechanical vibration of GIS. However, due to structural differences, the characteristics of circulating current in the three-phase insulated type GIS's enclosure and single-phase insulated type GIS's enclosure are completely different, resulting in different vibration mechanisms. Thus, the characteristics of circulating current in GIS's enclosure is analyzed firstly in this section, and the vibration mechanism is then analyzed with two methods: electrodynamic force and magnetostriction.

2.1. Characteristics of Circulating Current

Equivalent circuit diagram of GIS is shown in Figure 1 [18]. When AC current flows through an inner conductor, a circulating current is formed in GIS.



Figure 1. Circuit model of GIS.

In the equivalent circuit, Z_1 stands for leakage impedance of primary side (i.e., inner conductor), Z_2 stands for leakage impedance of secondary side (i.e., enclosure of GIS) and Z_m stands for excitation impedance. i_1 refers to as primary side current, i_2 refers to as secondary side current and i_m stands for excitation current. As the electromagnetic coupling between primary side and secondary side is relatively poor, this results in i_2 being smaller than i_1 ; however, i_2 and i_1 are in the same magnitude [18]. Literature [19] points out that the circulating current of 500kV GIL enclosure is about 75% of the conductor current.

Single-phase insulated type structure is often used in GIS equipment with high voltage levels (for example, 500kV GIS equipment) under normal operation conditions, and the circulating current is generated in the closed loop formed by the enclosure of GIS, frame and grounding grid. The loop includes two kinds: one is composed of the enclosure and grounding grid as illustrated in Figure 2; and one is composed of the enclosure of different phases and grounding grid as illustrated in Figure 3 [20]. In this case, i_2 is on the same number order as i_1 , as analyzed above.



Figure 2. Loop composed of enclosure and grounding grid.



Figure 3. Loop composed of different phase and grounding grid.

Three-phase insulated type structure is often used in GIS equipment with low voltage level, for example, 110 kV GIS equipment. In an ideal situation, the current in phase A, B and C is balanced; this means that the sum of current vectors is nearly zero. Thus, there is almost no circulating current. Although unbalance induced current always exists when GIS is in operation, as shown in Figure 4, in this case i_2 is still far smaller than i_1 [20].



Figure 4. Circulating current of three phase insulated type GIS.

To summarize, the circulating current of single-phase insulated type GIS is in the same magnitude as the current of the inner conductor, while the circulating current of three-phase insulated type GIS is much less than the current of inner conductor. One can observe that circulating current of the two types of GIS is completely different, which results in different vibration mechanisms.

2.2. Vibration Mechanism of Single Phase Insulated Type GIS

As the enclosure of GIS possesses good shielding effects, the inner conductor is not affected by other the two-phase conductor. This means that vibration of inner conductor itself is very small. However, many electrical components in GIS are connected by contacts, such as circuit breaker and isolating switch. When current flows through contacts, the direction of current line is changed; in other words, the current line shrinks near the contacts' surface to generate electrodynamic force, as shown in Figure 5, thereby causing vibrations of GIS.



Figure 5. Force analysis of contacts.

Assuming that the current flowing through contacts is $i_0 = I_0 \sin(\omega t)$, in which ω is current frequency and I_0 is current amplitude, the electrodynamic force caused by contacts can be expressed as Equation (1) in which *a* is the radius of contacts spot, *D* refers to the diameter of contacts surface, *F* denotes electrodynamic force, P_j denotes initial pressure acting on contact, H_b denotes cloth hardness of the material, ζ denotes the deformation coefficient of material between 0.3 and 1, and μ_0 is the permeability of vacuum [2].

$$F = \frac{\mu_0 I_0 \sin^2(\omega t)}{4\pi} \ln\left(\frac{D}{2a}\right) \tag{1}$$

$$a = \sqrt{\frac{P_j}{\pi \zeta H_b}} \tag{2}$$

On the other hand, enclosure is in the magnetic field generated by the inner conductor. As mentioned above, the circulating current in the enclosure (i.e., i_1) is in the same magnitude as the current of the inner conductor (i.e., i_0); that is, electromotive force exists between enclosure and inner conductor, as shown in Figure 6.



Figure 6. Force analysis of single phase insulated type GIS.

Assuming that radius of enclosure is R, which is far larger than the thickness of enclosure, magnetic field B_R in enclosure can be considered equal as expressed in Equation (3). The electrodynamic force is shown in Equation (4) [20].

$$B_R = \frac{\mu_0 i_0}{2\pi R} = \frac{\mu_0 I_0 \sin(\omega t)}{2\pi R}$$
(3)

$$F_1 = B_R i_1 L = \frac{\mu_0 k L I_0^2 \sin^2(\omega t)}{2\pi R}$$
(4)

It is observed that vibration caused by electrodynamic force consists of two parts: contacts and enclosure. The frequency is twice of ω ; that is, when frequency of the current is 50 Hz, frequency of the vibration signal is 100 Hz. Meanwhile, experimental results show

2.3. Vibration Mechanism of Three Phase Insulated Type GIS

An alternating magnetic field is generated by a three-phase inner conductor, and as mentioned above the circulating current is very small; that is, the electromotive force between the enclosure and the inner conductor is small. However, the electrodynamic force exists between three phase inner conductor. This is the significant difference of the vibration mechanisms between these two kinds of GIS.

Phase A is taken as an example to analyze electrodynamic force, as illustrated in Figure 7 [2,21]. The current of the three-phase can be expressed as Equations (5)–(7).

$$i_a = I_0 \sin(\omega t) \tag{5}$$

$$i_b = I_0 \sin(\omega t + 120^\circ) \tag{6}$$

$$i_c = I_0 \sin(\omega t + 120^\circ) \tag{7}$$

 l_{ab} , l_{bc} and l_{ac} denote the distance between phase A–B, phase B–C and phase A–C, respectively. θ is angle between f_{ab} and f_{ac} , and it can be obtained according to cosine theorem, as shown below.

$$\cos\theta = \frac{l_{ab}^2 + l_{ac}^2 - l_{bc}^2}{2l_{ab}l_{ac}}$$
(8)



Figure 7. Force analysis of three phase insulated type GIS.

The electrodynamic force of phase A is shown below.

$$f_{ab} = \frac{\mu_0 L I_0^2 \sin(\omega t) \sin(\omega t - 120^\circ)}{2\pi l_{ab}}$$
(9)

$$f_{ac} = \frac{\mu_0 L I_0^2 \sin(\omega t) \sin(\omega t + 120^\circ)}{2\pi l_{ac}}$$
(10)

$$f_a^2 = f_{ab}^2 + f_{ac}^2 + 2f_{ab}f_{ac}\cos\theta$$
(11)

Considering the actual situation, let $l_{ab} = l_{ac} = l_{bc} = l$, and the force of *L* length inner conductor is shown in Equation (12). It is observed that the frequency of the electrodynamic force is also twice of ω . Experimental results show that harmonic components will appear in vibration signals when there is a mechanical defect.

$$f_a = \frac{\sqrt{3}\mu_0 L I_0^2 |\sin(\omega t)|}{4\pi l} \tag{12}$$

To summarize, vibration caused by electrodynamic force consists of two parts: contacts and inner conductor. This is the biggest difference of single-phase insulated type GIS.

2.4. Vibration Mechanism of Magnetostriction

Magnetostriction effect in core coil equipment can also cause vibration in GIS. Set $U_1 = U_0 \sin(\omega t)$, and the magnetic flux intensity in iron core can be expressed as Equation (13) in which *N* refers to coil turns and *S* refers to core cross-sectional area [21].

$$B = \frac{U_0 \cos(\omega t)}{\omega NS} = B_0 \cos(\omega t) \tag{13}$$

$$B_0 = \frac{U_0}{\omega NS} \tag{14}$$

Considering that the magnetic flux density varies linearly with the magnetic field strength, the magnetic field strength can be expressed as Equation (15) in which B_s is saturation magnetic induction intensity, and H_c is coercivity.

1

$$H = \frac{B}{\mu} = \frac{BH_c}{B_s} = \frac{B_0 H_c \cos(\omega t)}{B_s}$$
(15)

When an alternating magnetic field exists, the micro deformation of ferromagnetic material is expressed as Equations (16) and (17) in which ε and ε_s refer to axial magnetostriction rate and saturation magnetostriction ratio, respectively, and L and ΔL refer to the original axial dimension and extension of silicon steel in the axial direction, respectively.

$$\varepsilon = \frac{\Delta L}{L} \tag{16}$$

$$\frac{\Delta L}{L}\frac{1}{dH} = |H|\frac{2\varepsilon_s}{H_c^2} \tag{17}$$

 ΔL is shown in Equation (18), and the vibration acceleration caused by magnetostriction can be obtained by Equation (19).

$$\Delta L = L \int_0^H |H| \frac{2\varepsilon_s}{H_c^2} dH = \frac{\varepsilon_s L U_0^2 \cos^2(\omega t)}{(\omega N B_s S)^2}$$
(18)

$$a = \frac{d^2 \Delta L}{dt^2} = -\frac{2\varepsilon_s L U_0^2 \cos(2\omega t)}{(NB_s S)^2}$$
(19)

It is observed that the frequency of vibration acceleration is twice of ω ; that is, when the frequency of the current is 50 Hz, the frequency of the vibration signal is 100 Hz. However, due to the nonlinearity of core material, there are many higher harmonic components in vibration signal, including 200 Hz, 300 Hz, 400 Hz and so on.

To summarize, the vibration of single phase insulated type GIS includes three parts: enclosure vibration, contacts vibration and vibration caused by magnetostriction. The vibration of three-phase insulated type GIS includes three parts: inner conductor vibration, contacts vibration and vibration caused by magnetostriction. This is the biggest difference between two type GIS.

3. Experiments and Vibration Data Analysis

3.1. Experiment Platform and Detecting System

The test is conducted on a 110 kV GIS experiment platform filled with SF_6 , including two bushing, two bus and one isolation switch; all components of the platform are true

equipment used for simulating the actual situation, as shown in Figure 8. The current generator can generate a continuously current from 0 A to 3000 A. A vibration detection system is developed to collect and process data, including acceleration sensor, acquisition card and PC. PCB333B50 is selected as acceleration sensor, and its frequency response is from 0.5 Hz to 3000 Hz, sensitivity is 1000 mV/g and measurement range is from -5 g to +5 g. The model of acquisition card is NI9234, and it is a four-channel dynamic signal acquisition module with a precision of 24 bits, and the sampling rate is set as 25.6 kS/s. Vibration data are transmitted to PC for further analysis after being recorded by the acquisition card.



Figure 8. GIS vibration experiment system. (a) Experimental setup. (b) Physical object of test platform.

In order to study the vibration characteristics under different contact states, three types of cases are set up by changing the state of the isolation switch, including normal, mild poor contact and serious poor contact, as shown in Figure 9. As the vibration wave is a mechanical wave, which decays gradually in the process of propagation, it is necessary to install the acceleration sensor closer to the defect source in order to obtain better detection effects [22]. Thus, all vibration tests are carried out on the top of the enclosure, directly above the defect.



Figure 9. Mechanical defects setup. (a) Normal case; (b) mild poor contact; (c) serious poor contact.

3.2. Vibration Data Analysis

3.2.1. Time Domain Analysis

As the current affects vibration characteristics of GIS equipment seriously, four kinds of current are set for each contact state, including 500 A, 1000 A, 1500 A and 2000 A. It should be noted that the vibration test is susceptible to external interference, and there exists some discreteness in the test data. External vibration sources should be excluded during the test, and abnormal data should be eliminated. Finally, for each state, five groups of vibration data are saved in the steady state, and the acquisition time of each group is 1 s.

The first 0.2 s part of typical time domain waveform is extracted to study vibration characteristics under different conditions, as shown in Figure 10. It is obvious that amplitude of vibration signal increases with the current, and vibration signal shows strong periodicity. When the current is 500 A, the different between three kinds of contact state is small. When current increases to 1000 A, 1500 A and 2000 A, it can be found that the

vibration signal under a serious poor contact state is the largest and, under normal state, is the smallest; it is feasible enough to distinguish the contact state of GIS equipment from the time domain waveform when the current is big.



Figure 10. Time-domain waveform under different case.

Considering the dispersion of vibration signal, the mean and standard deviation of five groups of data are counted, the amplitude of vibration signal under different states is shown in Figure 11. It is illustrated that the amplitude increases gradually with the current, and three different contact states have the same increasing trend. When current is 500 A, the amplitude is small and the difference is relatively small. However, when the current is larger, it is easier to diagnose the contact state by comparing the amplitude of vibration signal. That is, a large current is more beneficial for diagnosing mechanical defects.



Figure 11. Comparison of acceleration under different cases.

3.2.2. Frequency Domain Analysis

Figure 12 shows the typical frequency domain waveforms of vibration signal under a normal case. It can be observed that, when the current is 500 A, the main energy of vibration signal is concentrated below 600 Hz. When the current is 1000 A, there are some higher frequency components such as 700 Hz and 800 Hz. When the current increases to 1500 A and 2000 A, the frequency distribution becomes wider towards 1200 Hz. At the same time, the amplitude of each frequency component increases with the current. Figure 13 shows the frequency domain waveforms under mild poor contact case. It is observed that frequency range is beyond 600 Hz when current is 500 A, and the frequency distribution becomes wider towards 1300 Hz when current increases to 1500 A and 2000 A, and there is an increasing trend in amplitude. The frequency domain waveforms under



serious poor contact case are shown in Figure 14, and frequency distribution range and amplitude show the same trend as the former.

Figure 12. Frequency domain waveforms under the normal case: (**a**) 500 A; (**b**) 1000 A; (**c**) 1500 A; (**d**) 2000 A.



Figure 13. Frequency domain waveforms under the mild poor contact case: (**a**) 500 A; (**b**) 1000 A; (**c**) 1500 A; (**d**) 2000 A.



Figure 14. Frequency domain waveforms under the serious poor contact case: (**a**) 500 A; (**b**) 1000 A; (**c**) 1500 A; (**d**) 2000 A.

To summarize, when the contact condition deteriorates, the frequency spectrum range becomes wider, and increased energy is concentrated at higher frequency components. The amplitude of each frequency component becomes bigger. When the current increases gradually, there are more high frequency components, and the amplitude also becomes bigger.

The waveform distortion rate (THD) reflects the distortion degree of a signal waveform relative to the sinusoidal waveform, which can be used to describe the influence of higher harmonics component on vibration signal waveform [23]. In this paper, THD can be calculated by power spectrum of vibration signal, as shown in Equations (20)–(24). In the formulas, v(t) ($0 \le t \le 1$ s) represents vibration signal, τ refers to displacement variable ($0 \le \tau \le 1$ s), $F(\tau)$ denotes the autocorrelation function of v(t) and P(f) refers to power spectrum.

$$F(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-\infty}^{+\infty} \nu(t)\nu(t+\tau)dt$$
(20)

$$P(f) = \int_{-\infty}^{+\infty} F(\tau) e^{-i2\pi f\tau} dt$$
(21)

$$A_{100} = P(f)|f = 100 \tag{22}$$

$$A_k = P(f)|f = 100k \tag{23}$$

$$THD = 20 \log \left(\frac{1}{A_{100}} \sqrt{\sum_{k=2}^{f_{100}^1 - 1} (kA_k)^2} \right)$$
(24)

Considering the dispersion of vibration signal, the mean and standard deviation of five groups of THD are counted, as illustrated in Figure 15. THD increases with the increase in contact deterioration degree. When current becomes large, the growth trend of THD slows down gradually. That is, it is feasible to distinguish different contact states by comparing THD.



Figure 15. Comparison of waveform distortion ratio under different case.

To summarize, mechanical defects can be diagnosed by analyzing signal amplitude, frequency spectrum and waveform distortion rate. The greater the current, the better the effect.

4. Field Application

Vibration detection on GIS equipment was carried out in one 220 kV substation, as mechanical defects are mainly caused by poor contact, unbalanced alignment of the conductor and components' looseness and so on. Thus, vibration test points are often located near joint parts, such as the circuit breaker, isolation switch and contact. One abnormal signal is found in an isolation switch, and on-site detection is shown in Figure 16.



Figure 16. The location of the vibration measuring point.

Figure 17 shows the typical time domain waveform of vibration signal of a 220 kV isolation switch, and it can be observed that the vibration signal shows strong periodicity, and there is a big difference between phase A, B and C. In order to eliminate the dispersion of test results, five groups of vibration data are recorded, and the acquisition time of each group is 1 s. The amplitudes of phase A and phase B are similar, which are smaller than that of phase C, as shown in Figure 18. At the same time, there is obvious distortion in the waveform of phase A and phase C, and the distortion of phase of B is relatively small. It can be concluded that there may be abnormality in phase C.



Figure 17. Time-domain waveform of isolation switch. (a) Phase A; (b) Phase B; (c) Phase C.



Figure 18. Comparison of acceleration.

Figure 19 shows the typical frequency domain waveforms of a vibration signal, and it can be observed that the main energy of phase A is concentrated at 100 Hz and 300 Hz,

and there are some components at 500 Hz, 700 Hz and 800 Hz. The main energy of phase A is concentrated at 100 Hz, and the amplitudes of 200 Hz, 300 Hz, 500 Hz and 600 Hz are relatively small. However, the frequency spectrum of phase C is relatively wide, and the amplitude is relatively large. It contains many higher components, such as 300 Hz, 400 Hz, 500 Hz and 800 Hz. The 300 Hz component is the largest, and the 100 Hz component is larger than that of phase A and phase B. The THD of phase A, B and C is illustrated in Figure 19d, and it is observed that phase B is the smallest (close to -28 dB), phase A is the second (nearly -8 dB) and phase C is the largest (close to 18 dB); that is, the situation of phase C is the worst.

As phase A and phase C are symmetrically distributed, the structure of the three-phase is the same, and the load across all of them are similar; thus, the vibration characteristics of the three-phases are comparable. By comparing time domain and frequency domain waveform, it can be concluded that there is some abnormality in phase C. In the outage maintenance test, results show that the loop resistance of phase C is obviously higher than the other two phases, which is confirmed by vibration test results, demonstrating that abnormal diagnosis can be realized by the method proposed in this paper.



Figure 19. Frequency domain waveform of isolation switch. (**a**) Phase A; (**b**) Phase B; (**c**) Phase C; (**d**) comparison of all three phases.

5. Conclusions

Detection and diagnosis technologies of mechanical defects based on vibration signal are studied in this paper, including theoretical analysis, experimental research and field application. The results show the following.

- 1. GIS equipment structure lends to different vibration mechanism. The vibration of single-phase insulated type GIS includes three parts: enclosure, contacts and magnetostriction. The vibration of three-phase insulated type GIS includes three parts: inner conductor, contacts and magnetostriction.
- 2. Mechanical defects can be diagnosed by analyzing signal amplitude, frequency spectrum and waveform distortion rate. When the current is small, the change of signal

amplitude is not as obvious as the frequency spectrum and waveform distortion rate. A large current is more beneficial for diagnosing mechanical defects.

3. Field application demonstrates the feasibility and effectiveness of detection and diagnosis technology for mechanical defects based on vibration signal. Abnormal diagnosis can be realized by the methods proposed in this paper. In the future, we will carry out more field applications and accumulate data in order to lay a foundation for applying artificial intelligence to mechanical fault diagnosis.

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