ISSN: 2472-3703 DOI: 10.6911/WSRJ.202402_10(2).0001

A Review of Wind Turbine Bearing Fault Diagnosis

Yanjun Li[1, a, *]

[1]School of Electronic and Information Engineering, University of Inner Mongolia, Hohhot, China

[a]32256131@mail.imu.edu.cn

Abstract

This paper provides a comprehensive review of the latest research progress in intelligent diagnosis and prediction technologies for wind turbine bearing faults. It covers several key areas, including monitored object selection, signal processing and feature extraction, and the application of pattern recognition and deep learning for fault diagnosis. The paper thoroughly summarizes current research hotspots and development trends in this field. At the same time, it points out that China still faces challenges in aspects like automation, localization, and data acquisition for bearing fault diagnosis, and proposes feasible solutions. Overall, this paper lays a theoretical foundation for further research into bearing failure mechanisms and intelligent diagnosis technologies. It holds important academic value and application prospects, as it can promote health management and fault prediction technologies for wind turbines. The paper serves as a useful reference for advancing technologies in this domain.

Keywords

Wind turbine, Bearing, Fault diagnosis.

1. INTRODUCTION

In recent years, renewable energy has received widespread attention globally, which is inseparable from the urgent need to address climate change today. Among them, wind power, as a clean and renewable energy, has huge development potential[1]. Extensive research has shown that compared to traditional fossil fuels, wind power generation can significantly reduce greenhouse gas emissions and have little environmental impact[2]. In recent years, with the advancement of wind power generation technology and the decline in wind turbine costs, global wind power installed capacity has maintained a rapid growth trend[3]. According to the forecast of the Global Wind Energy Council (GWEC) in its "2021 Global Wind Report[4]", the global wind energy market will add 557GW of new capacity in the next five years, and annual new capacity additions will exceed 110GW by 2026[5]. As a country with relatively abundant wind energy resources, China also attaches great importance to the development of wind power and has become one of the largest wind power markets globally[6].

With the rapid growth of wind power scale, wind turbine generators have become key equipment in modern renewable energy systems. However, various failures will occur in generators during long-term operation, seriously impacting the economic and social benefits of wind farms[7]. Bearing failures, in particular, are one of the major causes of wind turbine damage[8]. Bearing failures not only directly reduce generating efficiency and increase maintenance costs, but may also lead to further mechanical failures or even accidents if not detected and handled in a timely manner, threatening the safe operation of wind farms. Therefore, improving bearing failure prediction and diagnosis technologies to accurately locate and warn of failures is important for avoiding failure expansion and reducing unit losses.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202402_10(2).0001

Bearing intelligent fault diagnosis and prediction technologies that can realize predictive maintenance are more economically effective and better aligned with the development direction of the wind power industry compared with post-maintenance[9]. A thorough study of bearing failure mechanisms and characteristics, and the development of highly sensitive fault detection methods, as well as the establishment of precise and reliable fault classification and prediction models, are key to realizing wind turbine status monitoring and fault prediction[10]. Continuous innovation and improvement in bearing fault diagnosis and prediction technologies will promote the development of wind turbine generators towards higher reliability and lower maintenance costs, which is of great significance to comprehensively improve the utilization efficiency of wind power. Based on this, this paper reviews relevant academic research on wind turbine generator bearing fault diagnosis.

2. MONITORING TARGETS OF WIND TURBINE GENERATOR BEARING FAILURES

Wind turbine generators mainly used in China's wind power sector are double-fed asynchronous wind power generators, in which the main shaft bearing is an important component of the drive system. To monitor the main bearing of wind turbine generators, the vibration signal, acoustic signal, temperature parameters and SCADA parameters generated by the main bearing can be detected to diagnose and analyze failures of the main shaft bearing of wind turbine generators.

2.1. Vibration Signals

Vibration signal analysis is a commonly used method for fault diagnosis. By monitoring and analyzing the vibration signals generated by the wind turbine generator system, the frequencies and vibration characteristics related to faults can be identified to determine whether there are any faults in the system. Vibration signal analysis methods include time domain, frequency domain and time-frequency domain analysis. Commonly used feature extraction methods include wavelet transform and empirical mode decomposition. Vibration signals have the advantages of real-time monitoring, easy data collection, rich frequency band information and effective reflection of mechanical fault information. However, they are also affected by other vibration sources and are prone to signal interference. In addition, fault features are not obvious in the initial operation period of equipment, making them difficult to detect.

Qi Yongsheng[11] realized non-intrusive diagnosis through vibration analysis, reducing damage to mechanical components of equipment. Due to less background noise interference, vibration analysis has been widely used in fault diagnosis. In actual wind farms, in order to obtain vibration signals of main shaft bearing failures, accelerometers need to be installed on the main shaft bearing and vibration data collection points need to be set up. Traditional morphological filtering methods may be interfered by internal noise frequencies when processing signals with failure impact characteristics, leading to not obvious extracted fault information. To address this issue, an improved envelope derivative energy operator was introduced. This operator combines envelope analysis and derivative energy operator to effectively extract envelope information of signals and highlights fault features. In complex noisy environments, this improved method can enhance fault features and improve the accuracy and reliability of fault detection. Therefore, this method has wide potential applications in practical engineering and is expected to provide strong support for related research and practice fields.

Fan Ji[12] mentioned that in order to determine the operating status of the main shaft bearing of a wind turbine generator, it is necessary to analyze the vibration signal data collected by the accelerometer installed on the main shaft bearing. However, due to the nonlinear and non-

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202402_10(2).0001

stationary characteristics of the vibration signals of the wind turbine generator main shaft bearing, and the presence of a large amount of noise in actual measurements, it is necessary to clean the raw vibration signals to better extract their characteristic information. The improved method shows significant advantages in identifying bearing fault types. Compared with traditional methods, the accuracy is significantly improved, the correct identification of fault types increases, and the misdiagnosis rate decreases. In addition, the improved method can complete fault diagnosis in a shorter computing time, accelerating the generation of diagnostic results and helping real-time equipment status monitoring and timely response measures.

Xie Lirong[13] proposed a new method for fault diagnosis of wind turbine generator main bearings. This method first extracts feature information as the input of classifiers and diagnoses faults of wind turbine generator main bearings using machine learning methods. To improve the diagnosis accuracy and efficiency, the study constructed a feature selection and parameter optimization model based on genetic algorithm (Genetic Algorithm, GA) and ENN (Edited Nearest Neighbor). It processed feature sets of compound fault mixing domains including time domain, frequency domain and time-frequency domain for failures of double-fed wind turbine generator bearings, and put forward a new idea and method to eliminate the interference of redundant or irrelevant information.

Xiang Ling[14] proposed an improved fault diagnosis method for rolling bearing faults of wind turbine generators to improve the reliability of vibration signal diagnosis and refinement of feature extraction methods. The method combines multi-point optimal adjustment of minimum entropy deconvolution and 1.5-dimensional energy spectrum to effectively extract composite fault features, which is applicable to strong background noise environments. However, the processing of this method is relatively complex and requires iterative selection of filters. This iterative process may result in the selected filter only achieving local optimal rather than global optimal. At the same time, the method is also limited by too many model parameters and a complex resampling process, which may increase complexity and computational costs in practical applications.

2.2. Acoustic Signal Parameters

The acoustic signal collection apparatus was flexibly deployed with low cost, enabling early failure detection capabilities. However, the acoustic signals tended to be rather faint, and were prone to interference from background noise, rendering the extraction of fault features quite arduous. Additionally, the detection results remained highly susceptible to environmental influences.

Lü Fengxia[15] addressed the challenges associated with the extensive data volume, time-consuming processing, and dependence on detection personnel for fault type identification when employing acoustic emission technology. To tackle these issues, a feature extraction method based on improved adaptive noise-aided empirical mode decomposition was proposed. This method not only exhibits advantages in feature extraction but also offers feasibility for achieving automated fault diagnosis, thereby reducing the interference of subjective factors. Therefore, this study holds significant academic value and practical application prospects in the field of industrial equipment fault diagnosis and prediction.

In recent years, the structure of wind turbine generators has become increasingly complex, imposing more stringent requirements on sensor placement. In the intelligent fault diagnosis of bearings, acoustic signals have garnered widespread attention due to their non-contact, easy-to-deploy, and cost-effective advantages. However, the strong environmental noise within wind turbines hinders traditional bearing fault diagnosis methods from accurately extracting the features of acoustic signals. To address this issue, Wang Jinrui[16] proposed an effective sparse feature extraction method capable of handling acoustic signals in the presence of strong noise without the need for any denoising preprocessing. This method can precisely classify different

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202402_10(2).0001

bearing faults, providing significant promotional value for the engineering application of bearing acoustic signals in intelligent fault diagnosis.

While the proposed method has shown promising results in acoustic signal processing, its diagnostic accuracy still lags behind that of vibration signals. Therefore, one of the future research priorities is to enhance the diagnostic precision of acoustic signals. This may involve refining feature extraction methods, identifying more discriminative features, or further optimizing algorithm parameters. Additionally, the introduction of other signal processing techniques, such as time-frequency analysis, wavelet transformation, etc., could be considered to comprehensively explore fault information within acoustic signals.

In the field of wind turbine generators, there exists significant potential for intelligent fault diagnosis using acoustic signals. By refining and optimizing acoustic signal processing methods, more precise and reliable fault diagnosis can be achieved, thereby enhancing the reliability and safety of turbine units. Furthermore, acoustic signals, as a non-contact and easily deployable sensing method, offer broad application prospects in the wind power industry. Therefore, this study holds substantial significance and value for both academic research and engineering applications.

2.3. Temperature Parameters

Presently, research has achieved certain milestones in the field of wind turbine fault diagnosis, predominantly focusing on vibration signals, with limited attention given to temperature parameter-based diagnostics. Temperature parameter monitoring is primarily employed to detect variations in the temperature of the main bearings or oil temperature in wind turbine generators. Fault diagnosis can be conducted through techniques such as deep learning, artificial intelligence algorithms, and simulation. These approaches not only offer a direct reflection of thermal anomalies but are also convenient to measure, enabling the early detection of faults. Additionally, temperature parameters can be integrated with other fault diagnosis results. By observing temperature changes in the gearbox, effective diagnosis of various faults in wind turbine generators can be realized. However, the response of temperature parameters is lagging, making it challenging to precisely locate faults, and it is susceptible to environmental temperature influences.

Wan Anping[17] proposed a novel method for predicting and warning of wind turbine main bearing temperatures, aiming to timely detect temperature faults in wind turbine generators. This method is based on the XGBoost-KDE model. Experimental data analysis demonstrates that, under normal operating conditions, the main bearing temperature prediction model can accurately estimate real-time temperatures and sensitively capture temperature changes caused by main bearing faults. Therefore, effective warning and maintenance of the wind turbine main bearing can be conducted one month before the occurrence of a fault. This method has a positive impact on the operation and maintenance of wind farms. By providing early warnings of main bearing faults, wind farms can better plan and allocate maintenance resources, minimizing downtime and enhancing the availability and efficiency of wind turbine generators. Furthermore, the high-precision predictions of this method contribute to the timely identification of other potential issues that may impact turbine performance, further optimizing the operational management of wind farms.

In order to prevent failures in the generator main bearings caused by prolonged high-temperature operation, leading to a decrease in lubricating oil viscosity, increased friction, and elevated temperatures, it is crucial to effectively predict the main bearing temperature. Liu Jie[18] constructed a main bearing temperature prediction model based on the LSTNet network. This model utilizes grey relational analysis to select feature parameters with strong correlation to main bearing temperature as observation vectors, thereby enhancing the accuracy and

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202402_10(2).0001

robustness of the prediction model. This provides theoretical support and a data foundation for subsequent generator bearing fault diagnosis and early warning.

Zhang Shaodong[19] proposed three measurement methods for the temperature of high-speed train unit bearings based on the MMR algorithm. Through multivariate normality and data covariance analysis, reasonable confidence intervals were established. Utilizing the least squares method for estimation, a bearing temperature fault prediction model was constructed. The application of this model can significantly reduce maintenance time, decrease the number of maintenance personnel, and lower bearing spare parts inventory for high-speed train units. Consequently, it reduces maintenance costs and lowers the million-kilometer failure rate caused by bearing faults, enhancing the operational reliability of high-speed train units. Although this method was studied for high-speed train unit bearings, it holds important reference significance for wind turbine generator bearings as well.

2.4. SCADA System Parameters

SCADA systems can monitor the operation of various components in wind turbine generators and acquire parameters such as output power, wind speed, power factor, etc. However, the use of SCADA systems is limited in small-scale wind farms. They require extensive data support for research and have complex parameters that are challenging to handle.

In order to identify the fault status of the generator drive-end bearing in wind turbine generators, Zhang Chao[20] proposed a novel diagnostic method in 2022. This method is based on cointegration theory and vector error correction model, utilizing multiple temperature parameters collected by the wind turbine generator SCADA system. A mathematical model is established to describe the relationships among these parameters, encompassing both long-term stability and short-term dynamics. Through cointegration tests on the temperature parameters, the method validates their meaningful correlations. However, due to the complexity of wind turbine generator systems and the diversity of SCADA parameters, further verification and refinement are still required for the consistency of this method across different components.

To address the challenges of numerous SCADA parameters and the difficulty of data cleansing, Xia Hemin[21] proposed the following improvement measures: Firstly, employing the Grey Relational Analysis (GRA) algorithm to reduce dimensionality of the initial SCADA data. The data preprocessing involves normalization to eliminate the influence of dimensional differences among various data indicators. Secondly, introducing the Sparrow Optimization Algorithm based on Firefly Improved Algorithm (FASSA) to optimize the prediction model. Ultimately, a wind turbine active power prediction model based on GRA-FASSA-KELM is constructed. After data cleansing, this method demonstrates improved predictive performance, confirming the effectiveness of data cleansing. It is important to note that the data cleansing model is built based on the common characteristics of a specific batch of turbines in the wind farm. While its feasibility has been validated in this wind farm, further verification is necessary to generalize its application to turbine data from other wind farms.

3. PATTERN RECOGNITION PLAYS A SIGNIFICANT ROLE IN THE DETECTION OF MAIN BEARING FAULTS IN WIND TURBINE GENERATORS

Pattern recognition methods aim to accurately identify and classify different types of main bearing faults. This is achieved by analyzing the vibration signals and features of the main bearings, with the following objectives:

(1) Fault Diagnosis: The primary objective is to determine whether there is a fault in the main bearing and identify the specific fault type, such as ball wear, cracks, looseness, etc. Accurate

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202402_10(2).0001

fault diagnosis facilitates timely implementation of maintenance measures, preventing further deterioration or triggering other faults.

(2) Fault Classification: Categorizing main bearing faults into different patterns or levels, such as minor faults, moderate faults, and severe faults. Through fault classification, the severity of the fault can be assessed, providing a basis for maintenance planning and resource allocation.

(3) Predictive Maintenance: By monitoring the vibration signals of the main bearing and utilizing the results of pattern recognition methods, it is possible to predict the development trend and remaining lifespan of main bearing faults. This aids in planning and scheduling maintenance activities, minimizing downtime, and reducing maintenance costs.
Indeed, pattern recognition methods are increasingly garnering attention.

Since the 1980s, artificial neural networks (ANN) have played a crucial role in pattern recognition algorithms. Modeled after the human neural network, ANN consists of numerous interconnected neurons, enabling it to process complex linear and nonlinear data. In practical engineering applications, adjusting the weights between neurons in ANN allows for various types of data processing, making it suitable for fault diagnosis in wind turbine generator main bearings. However, for scenarios involving small sample sizes, the training process of ANN requires tuning a multitude of parameters. Additionally, it may exhibit suboptimal training outcomes, making it challenging to meet the high-precision diagnostic requirements for wind turbine main bearings.

Due to the limitations of classical mathematical models that use only a single fault assessment indicator, they fail to comprehensively consider situations of abnormal main bearing temperatures. Consequently, analyzing each indicator individually becomes necessary, but establishing precise mathematical models in this manner proves challenging. In contrast, intelligent algorithms represent a black-box model; however, they require extensive data for training, posing a challenge due to substantial data demands needed to ensure model accuracy. Moreover, issues related to the deterministic nature of fault occurrence times and specific turbine units exist, sometimes requiring coverage of data across the entire range of operating conditions. Therefore, Chang Xingbang[22] employed an expert decision system and a relevant level matrix to determine the parameters influencing the severity of abnormal main bearing temperatures. By leveraging @RISK software and input from multiple experts, parameters closely correlated with abnormal main bearing temperatures were identified. In terms of application, only simulation experiments and exploratory reasoning have been conducted. Further research is needed to explore how these findings can be translated and utilized in specific engineering applications.

Building upon research in fuzzy recognition theory, Su Luwei[23] proposed a comprehensive fuzzy fault diagnosis process tailored for doubly-fed asynchronous generators in wind power systems. However, in the investigation of compound faults, this process has yet to be applicable in practical engineering, necessitating further research.

In order to address the issues of accuracy and time consumption in traditional multi-task rolling bearing fault detection methods, Zhang Xunjie [24] proposed a pattern recognition-based diagnostic approach for rolling bearing faults. Through experimental validation, this method demonstrated outstanding performance in identifying vibration signals associated with different fault positions and severity levels in rolling bearings. Its accuracy significantly surpassed commonly used deep learning and machine learning algorithms. The research holds promising prospects for improving the accuracy and efficiency of rolling bearing fault diagnosis, opening up new possibilities for research and practical applications in related fields.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202402_10(2).0001

4. CONCLUTION

The rapid development of the wind power industry has stimulated extensive research on wind turbine bearings by many scholars. Both domestically and internationally, researchers have proposed various methods and approaches. This paper comprehensively reviews and analyzes research content related to the monitoring objects, fault diagnosis, and artificial intelligence algorithms of wind turbine bearings. It summarizes and reflects on existing research results worldwide, providing a reference for subsequent research on wind turbine bearings. However, China's development in the technical research of wind turbine bearings is relatively late, and there are still many engineering and scientific problems that urgently need to be addressed. Therefore, a substantial amount of experimental and theoretical research is needed in the following areas:

1.Develop an automated fault diagnosis system to achieve full-process intelligence from signal acquisition to result output, reducing human involvement. Focus on the integration of sensor arrays, signal processing, and deep learning algorithms.

2.Research fault localization methods based on local measurement points, determining the fault location through the fusion of multiple sensors to provide guidance for maintenance. Emphasize research on sensor optimization configuration and signal fusion algorithms.

3.Construct a large-scale wind turbine operation dataset to provide rich training samples for deep learning models. Research on feature extraction, data augmentation, and related technologies is also needed.

4.Propose a full life cycle health management system based on digital twins, realizing fault prediction, state monitoring, and health assessment. Key aspects include modeling methods and optimization for model updates.

5.Conduct research on fault diagnosis and transfer learning across working conditions to improve the adaptability of models to new environments.

6.Explore a maintenance decision support system that visualizes early warning results to assist engineers in formulating maintenance strategies.

In conclusion, in-depth research on wind turbine bearing technology is necessary to cope with the rapid development of the industry and address practical engineering and scientific issues. More efforts and research are needed in areas such as data sharing, intelligent analysis, establishment of physical models, and fault diagnosis to promote the sustained development of the wind power industry.

ACKNOWLEDGMENTS

Funding Project: Major science and technology projects of Inner Mongolia Autonomous Region(2021ZD0019-4)

REFERENCES

[1] H.Xue, R.Z. Zhu: Assessment of Wind Energy Development, Utilization, and Layout Potential in China (Journal of Solar Energy, China 1990), p.1-11. (In Chinese)

[2] J. Varanasi and M. M. Tripathi: A comparative study of wind power forecasting techniques — A review article(2016 3rd International Conference on Computing for Sustainable Global Development, India 2016), p. 3649-3655.

[3] S.Yu,H.G.Yang: China’s provincial wind power potential assessment and its potential contributions to the “dual carbon” targets(Environ Sci Pollut Res 30,China 2023), p.13094–13117.

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202402_10(2).0001

[4] L.M.Li.Global Wind Energy Council: China Leads Global Offshore Wind Power Growth for Three Consecutive Years(China Energy News,China 2021),p.5-10.(In Chinese)

[5] X.Shi. By the End of 2031, Global Cumulative Installed Capacity of Offshore Wind Power Will Reach 370 Gigawatts(Mechanical and Electrical Business News,China 2022),p.7. (In Chinese)

[6] K.X.Xu. Secretary-General of the Global Wind Energy Council: China's Wind Power Installed Capacity May Become the World's Largest Within the Year(First Financial Daily,China 2010),p.2. (In Chinese)

[7] R.Kumar, M.Ismai, W. Zhao,et al. Damage detection of wind turbine system based on signal processing approach: a critical review, Clean Techn Environ Policy 23, vol. 20(2021),561–580.

[8] R.D.Gowdar, M.C. Mallikarjune Gowda. Reasons for wind turbine generator failures: a multi-criteria approach for sustainable power production, Renewables 3,vol.9 (2016).245-251.

[9] B.Liu,B.X.Bai,Q.B.Dai, et al.A review of bearing fault diagnosis for wind turbines, IOP Conference Series: Earth and Environmental Science,vol.67(2021),94-100.

[10] Do,M. Hung and Dirk Söffker. State-of-the-art in integrated prognostics and health management control for utility-scale wind turbines, Renewable and Sustainable Energy Reviews,vol.31(2021),n. pag.

[11] Y.S.Qi,J.Fan,Y.T.Li,et al. Bearing Fault Diagnosis Method for Wind Turbine Generator Based on Enhanced Morphological Filtering(Vibration and Shock, China 2021),p.212-220. (In Chinese)

[12] J.Fan,Y.S.Qi,X.J.Gao,et al. Bearing Fault Diagnosis for Wind Turbine Generator Based on Morphological Multifractal Analysis(Vibration, Testing, and Diagnosis, China 2021),p.1081-1089. (In Chinese)

[13] L.R.Xie,H.Yang,J.W.Jin,et al. Bearing Fault Diagnosis for Doubly Fed Wind Turbine Generator Based on GA-ENN Feature Selection and Parameter Optimization(Acta Energiae Solaris Sinica, China 2021),p.149-156. (In Chinese)

[14] L.Xiang,Y.Li.Research on Composite Fault Diagnosis of Rolling Bearings in Wind Turbine Generators(Acta Energiae Solaris Sinica, China 2021),p.90-97. (In Chinese)

[15] F.X.Lv,Y.Miao,F.F.Bie,et al.Application Research of ICEEMDAN and GS-SVM Algorithms in Fault Diagnosis of Rolling Bearing Acoustic Emission(Noise and Vibration Control, China 2022),p.92-97+129. (In Chinese)

[16] J.R.Wang,S.S.Ji,Z.Z.Zhang,et al.Fault Diagnosis of Bearings under Acoustic Signals using Parallel Sparse Filtering(Acta Aeronautica et Astronautica Sinica,China 2023),p.293-303. (In Chinese)

[17] A.P.Wan,Z.P.gong,Y.L.Zhang,et al.Temperature Prediction and Fault Early Warning for Wind Turbine Main Bearings Based on XGBoost-KDE(Thermal Power Generation,China 2022),p.164-171.(In Chinese)

[18] J.Liu,S.Q.Jiang.Research on Temperature Prediction of Wind Turbine Generator Main Bearings Based on LSTNet Network(Chinese Journal of Sensors and Actuators,China 2022),p.945-951.(In Chinese)

[19] S.D.Zhang,C.X.Pei,N.Li.Research on Fault Prediction Model for High-Speed Train Bearings' Temperature Based on MMR Algorithm(China Measurement & Test,China 2021),p.42-48.(In Chinese)

[20] C.Zhang,S.F.Zhang.Anomaly Identification Method for Wind Turbine Generator Drive-End Bearings Based on SCADA Temperature Data(Bearing,China 2022),p.67-73. (In Chinese)

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202402_10(2).0001

[21] H.M.Xia.Research on SCADA Data Processing and Cleaning Methods for Wind Turbines and Their Impact on Performance Prediction,North China Electric Power University (Beijing),(2022). (Master's thesis).

[22] X.B.Chang.Research on Detection and Diagnosis of Abnormal States in Wind Turbine Generator Main Bearing Temperature Based on Pattern Recognition,Xiangtan University,(2020). (Master's thesis).

[23] L.W.Su.Research on Fault Diagnosis Method of Wind Power Doubly Fed Asynchronous Motor Based on Fuzzy Recognition,North China Electric Power University,(2015). (Master's thesis).

[24] X.J.Zhang,M.Zhang,X.J.li.Fault Mode Recognition of Rolling Bearings Based on Two-Dimensional Images and CNN-BiGRU Network(Vibration and Shock, China 2021), p.194-201+207. (In Chinese)