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Design of an Edge Computing System for Wind Turbine Condition Monitoring and Diagnosis of Variable-Speed Operating Conditions

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Abstract: As wind turbines continue to grow in size and power density, issues such as drive system misalignment and the reliability of critical components have become increasingly prominent, posing major risks to the safe operation of wind farms. Traditional condition monitoring systems face bottlenecks such as closed data structures, fixed algorithms, poor monitoring timeliness, and difficulties in feature extraction under non-steady-state conditions. This paper designs and implements a browser-server (B/S) architecture-based edge condition monitoring device for wind turbines, aiming to establish an intelligent closed-loop monitoring system characterized by “data interconnection, autonomous algorithms, and proactive early warning.” The research includes the development of a hardware module supporting 24-bit high-precision synchronous acquisition of multi-source signals, and proposes a feature extraction method based on instantaneous angular velocity analysis and angular domain resampling for variable-speed operating conditions. Furthermore, through a collaborative edge-cloud architecture, the system enables dynamic algorithm updates and efficient access to massive amounts of data. Application validation at actual wind farms demonstrates that the system significantly improves fault detection accuracy and early warning response speed under complex operating conditions. This research not only provides a highly adaptable solution for the intelligent operation and maintenance of wind power equipment but also offers theoretical and practical support for the application of edge computing technology in industrial equipment.

Keywords: Edge computing; Fault diagnosis; Angular domain resampling.

1. Introduction

Against the backdrop of the global energy transition toward clean and low-carbon sources, wind power has become a core component of new energy strategies. Ensuring the long-term operational stability of large-scale wind turbines holds significant economic value and social importance. However, as wind turbines are subjected to alternating loads and extremely harsh environments over extended periods, their speed-increasing gearboxes and generators are highly prone to mechanical failures. Furthermore, traditional monitoring equipment often suffers from insufficient data transparency due to manufacturers’ technical barriers, making it difficult to meet users’ requirements for functional customization. Previous research has primarily focused on vibration signal analysis under steady-state conditions; however, it has limitations in addressing the frequency ambiguity issues caused by frequent start-stops and variable-speed operation of wind turbines, and lacks an efficient real-time computing system at the edge. The innovation of this study lies in the introduction of phase-frequency feature extraction technology based on speed key phases, as well as the innovative design of an order analysis algorithm that deeply integrates vibration and speed signals, effectively overcoming monitoring bottlenecks under non-steady-state conditions. The overall research scheme of the project is based on an open B/S architecture. By developing edge nodes with integrated high-performance computing capabilities, it achieves full-process collaboration ranging from high-precision physical signal sensing and on-site feature extraction to cloud-based model validation [1-3]. The aim is to establish a new monitoring system that is cross-platform compatible, provides transparent diagnostics, and possesses autonomous learning capabilities [4].

2. Research Purpose

With the rapid development of wind energy technology and the large-scale trend of wind turbines, the increase in single-machine capacity has significantly enhanced power generation efficiency, but at the same time, it has put forward higher requirements for the reliability of key components of the units. During long-term operation, mechanical faults such as shaft misalignment occur frequently, triggering cascading equipment damage and shutdown risks, which seriously threaten the safety and economy of wind farms. Although existing condition monitoring systems can identify such faults through vibration analysis, their applications still face multiple constraints: data silos, rigid functions, black-box diagnosis, and fragmented monitoring. To solve the above problems, this project designs an edge device for wind turbine condition monitoring. It breaks down data and hardware barriers through an open architecture, improves diagnosis transparency through reconfigurable algorithms, and compresses the fault response window through real-time monitoring. Finally, it forms an intelligent wind power monitoring closed loop of "data interconnection-algorithm autonomy-early warning preposition", providing a low-cost and high-adaptability active fault prevention and control solution for the industry [5-6].

3. Research Content

This project focuses on the research and development of an edge monitoring device for wind turbine conditions to solve the problems of solidified algorithm functions, insufficient data openness, and poor real-time monitoring timeliness existing in traditional CMS systems. The specific research contents are as follows:

3.1. Development of a high-precision multi-source signal synchronous acquisition system

A vibration signal synchronous acquisition module is designed based on a four-channel BNC interface, supporting the access of piezoelectric acceleration sensors with a range of ±50g, achieving 24-bit quantization accuracy and a maximum sampling rate of 128kHz. It integrates an IEPE conditioning circuit, is compatible with various speed sensors such as photoelectric encoders and reflective tape speed sensors, develops an instantaneous angular velocity analysis algorithm, and constructs a multi-dimensional data acquisition system including 1024Hz speed signal sampling [7-8].

3.2. Research on feature extraction algorithms under variable speed conditions

A shaft phase analysis model based on speed key phasors is established, and a spatiotemporal correlation algorithm for vibration signals and instantaneous angular velocity is developed [9-10]. The angular domain resampling technology is innovatively designed. Through the fusion of vibration-speed signals, order spectrum analysis under unsteady conditions is realized, breaking through the technical bottleneck of traditional spectrum analysis limited by speed fluctuations, and generating phase-frequency characteristic maps with a resolution of 0.25Hz.

3.3. Construction of an edge-cloud collaborative monitoring architecture

A B/S system supporting cross-platform deployment on Linux/Windows is developed, and an edge computing module including data acquisition, local storage (maximum 180-day rolling storage), and communication transmission (RESTful API /Modbus TCP) is designed. A server-side data management platform is developed to realize fast retrieval of 10^6 rows of data within 5 seconds, a remote push mechanism for algorithm models is constructed, and a Python script interpreter is supported to realize dynamic update of diagnosis rules.

3.4. Research on engineering application verification and migration models

The system reliability is verified through actual projects of Huaneng Clean Energy Research Institute, and a complete monitoring chain including 3300-XL-11 vibration sensors is established. A fault feature transfer learning model for planetary gearboxes is developed, a phase-frequency characteristic database is constructed, cross-unit diagnosis of common faults such as misalignment and gear pitting is realized, and a reusable fault pattern recognition case library is formed.

4. Innovations and Project Features

4.1. Shaft phase and phase-frequency feature extraction based on speed key phasors

Misalignment types of shafts have similar amplitude-frequency characteristics. The introduction of phase-frequency characteristics can obtain the vibration positions of two measuring points at the same time, providing basic information characterizing the type or severity of misalignment.

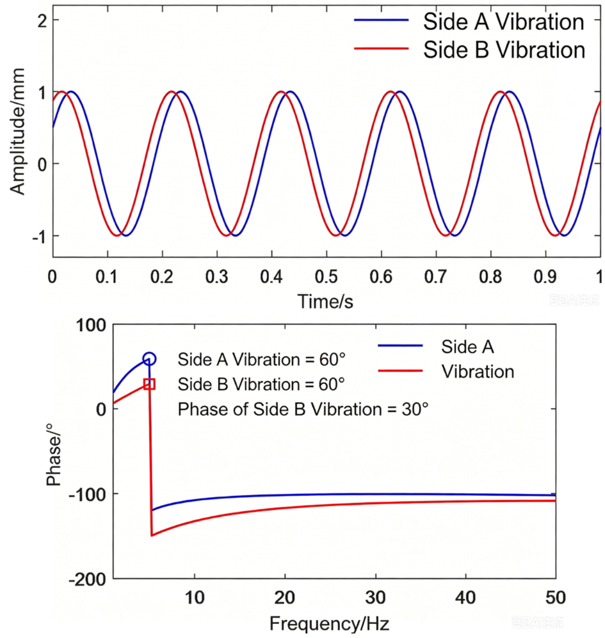

Figure 1. Schematic diagram of phase-frequency characteristics (vibration signals with 30° phase difference and phase-frequency curve)

Phase-frequency characteristics is shown in Figure 1.

4.2. Application of instantaneous angular velocity in misalignment fault vibration analysis

Instantaneous angle extraction is performed on signals output by various types of speed sensors. More detailed information about shaft motion or vibration can be obtained through instantaneous angular velocity information. As shown in Figure 2, when the unit is in the speed change process (e.g., speed-up stage), the instantaneous angular velocity signal shows that the shaft is in a fluctuating speed-up process, while the working speed can only reflect the operation trend of the shaft.

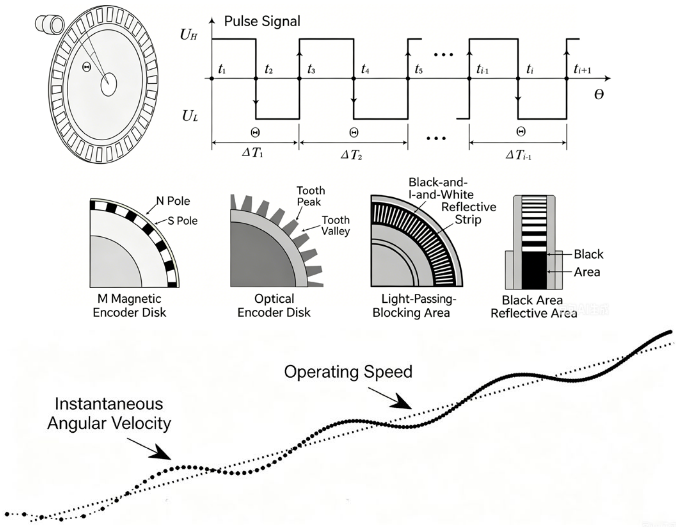

Figure 2. Schematic diagram of instantaneous speed extraction

Instantaneous speed extraction is shown in Figure 2.

4.3. Angular domain resampling and order analysis under variable speed conditions based on fusion of vibration and speed signals

It is a normal working condition for wind turbines to operate under unsteady speed. The characteristic frequency components of vibration signals during speed change are modulated by speed, resulting in frequency ambiguity. The monitoring device of this scheme is connected to piezoelectric acceleration vibration sensors and speed sensor signals at the same time, extracts instantaneous speed at a sampling rate of 1024Hz to obtain detailed information of speed changes, and fuses vibration signals and speed signals for analysis. The obtained angular domain vibration removes the order spectrum and phase-frequency characteristics affected by speed modulation on frequency, realizing real-time vibration analysis under any speed working condition.

Angular domain resampling and order analysis is shown in Figure 3.

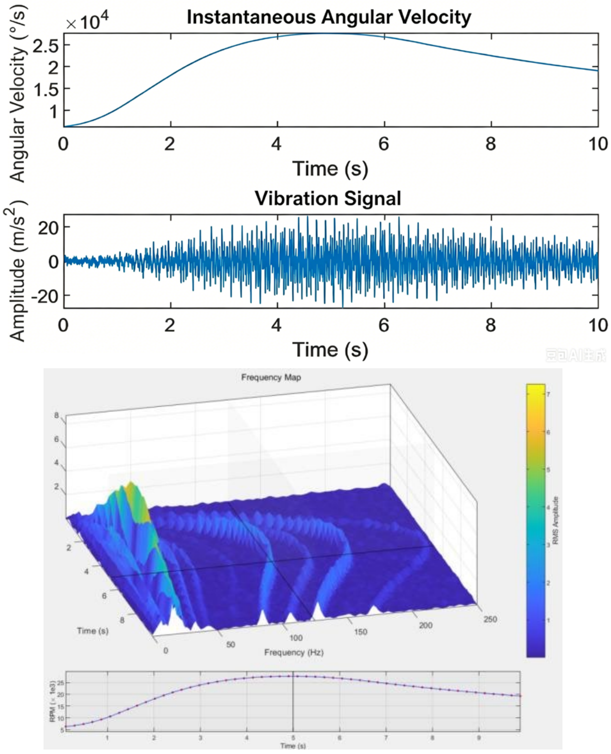

Figure 3. Angular domain resampling and order analysis

5. Technical Route, Problems to Be Solved and Expected Achievements

5.1. Technical Route and Problems to Be Solved

A wind turbine edge monitoring device is developed based on B/S architecture. Adopting speed key phasor feature extraction, instantaneous angular speed analysis and vibration-speed signal fusion technology, an intelligent monitoring system including vibration measuring points, speed measuring points, data storage and update strategies and RESTful API interfaces is constructed through high-precision data acquisition modules, edge computing nodes and cloud collaborative analysis. It aims to solve the five pain points of traditional CMS systems: heterogeneous data structure, solidified functions, closed hardware, black-box diagnosis and lagging monitoring, and overcome the implementation challenges of difficult engineering scenario adaptation and insufficient professional support.

5.1.1. Software Architecture of the Device

The software architecture of the device is shown in Figure 4, mainly composed of edge monitoring devices, data management and communication modules, service platforms, etc. The data of the edge monitoring device will be uploaded to the server through the wind farm ring network; at the same time, the server can manage and control the edge device and push algorithms.

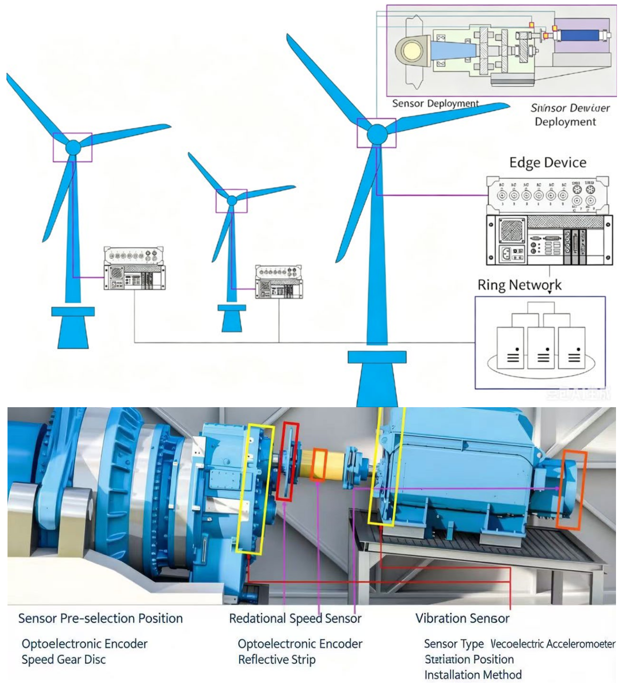

Figure 4. Overall architecture of wind turbine edge monitoring

Overall architecture of wind turbine edge monitoring is shown in Figure 4.

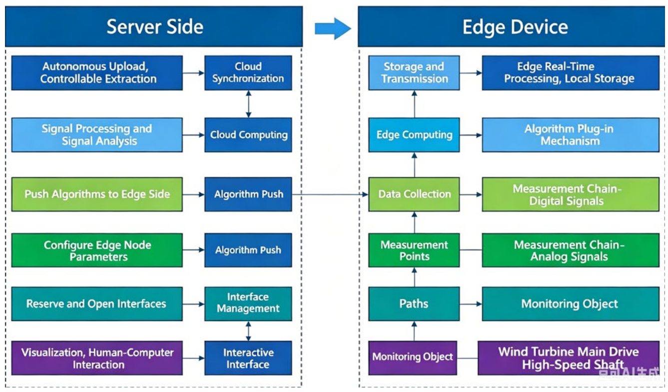

Figure 5. System structure diagram of server and edge monitoring device

System structure diagram of server and edge monitoring device is shown in Figure 5.

The data acquisition system can generate data sources by creating channels, and realize data analysis functions through serial/parallel functional modules of original data. This process can dynamically expand the computing nodes of the data chain according to the users data analysis requirements.

5.1.2. Hardware Composition of the Device

The hardware composition of the edge monitoring device mainly includes: speed and vibration information sensing unit, dynamic signal acquisition unit, edge computing module for signal analysis and feature extraction, function expansion and advanced application module, data communication module, and its structure diagram is shown in Figure 6.

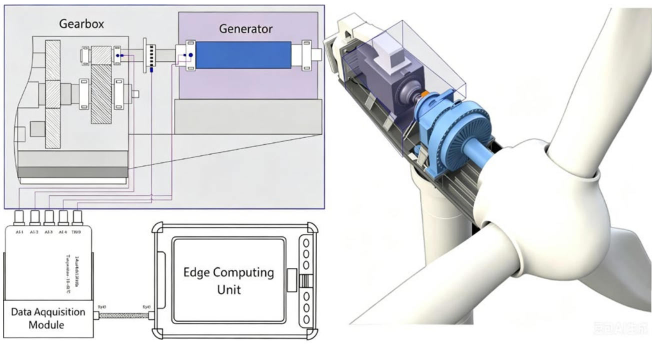

Figure 6. Schematic diagram of edge monitoring device

Schematic diagram of edge monitoring device is shown in Figure 6.

(1) Speed and vibration information sensing unit: The measurement chain for misalignment fault monitoring consists of 4 vibration measuring points and 1 channel speed measuring point. Two vibration sensors are installed on the high-speed shaft of the speed-increasing gearbox and the generator bearing seat of the wind turbine respectively, arranged horizontally and vertically, and the measuring points are positioned by magnetic base or bonding according to the site conditions; the speed measuring point can be led out from the encoder on the generator side, or a reflective tape is installed on the measured shaft section for speed measurement, and a customized speed sensor support is required for photoelectric speed measurement.

(2) Data acquisition module: With built-in IEPE conditioning function, it supports synchronous acquisition of vibration signals from piezoelectric acceleration vibration sensors, and the data acquisition module of a single edge monitoring device can be expanded in stages. For misalignment monitoring tasks, the amplitude resolution of data acquisition is 24bit, the maximum sampling rate is 128kHz, with high-resolution and high-precision sampling performance, as shown in Table 1; the data acquisition module has a built-in WEB console, which can perform real-time data protocol conversion, converting the collected data into mainstream specifications or protocols such as RESTful and Modbus TCP, facilitating data analysis and invocation of network service applications.

(3) Edge computing module: A functional platform between the physical monitoring object and industrial applications, integrating data storage, local computing power, network communication, algorithm models and other functions. Data analysis using the computing power of edge nodes is not affected by communication, and at the same time, it can share the computing load of the server computing platform, facilitating the realization of edge node-server online collaborative monitoring, and can be used as a data source for the server.

(4) Data storage and update strategy of the edge device: Taking 4 vibration signals of a single edge monitoring module at a sampling rate of 10kHz and 1 speed channel at a sampling rate of 1kHz as references, the edge monitoring device continuously stores the collected data, generating about 7GB of data per day. The data volume evaluation method is shown in Equation (1). The edge side supports storing complete monitoring data within a range of 1-180 days. Data exceeding the set data storage time range is updated according to the "first-in first-out" strategy, as shown in Figure 7, that is, data exceeding the storage time range will delete the earliest data with the earliest timestamp first.

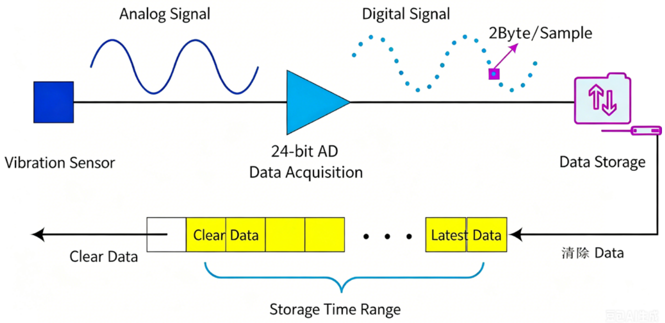

Figure 7. Data storage and update strategy

Data storage and update strategy is shown in Figure 7.

(5) Function expansion and advanced application module: The edge monitoring device has a built-in script program interpreter, which can change the monitoring task mode according to different monitoring tasks of the unit by pushing algorithms from the server or uploading algorithms locally, for monitoring and analyzing other components, improving the functional flexibility of the monitoring device. For example, after the misalignment fault of the unit is repaired, the monitoring and analysis of other key components can be realized through the above methods.

(6) Data communication module: The edge monitoring device monitors and analyzes the shaft misalignment status in real time locally without uploading all original data, thus greatly reducing the amount of transmitted data and the occupation of wind farm network transmission bandwidth. It can realize synchronous communication of unit status and key data between edge nodes and the server, and communication can adopt Rj45 network interface.

(7) Other components: Layout planning of measuring point wiring paths, armored protection of signal cables, customized production and installation of speed sensor brackets. Terminal blocks, cable slots, current-voltage conversion modules, power modules, etc. are selected according to actual needs. The current hardware solution uses wired sensors as measuring elements, which can be changed to wireless sensor hardware configuration according to actual needs.

5.1.3. Main Technical Indicators

The work clarifies the technical indicators from three aspects: acceleration vibration signal, speed signal and data acquisition performance, as shown in Table 1, Table 2 and Table 3.

Table 1. Technical indicators of acceleration vibration signal

Parameter Name	Parameter
Frequency response characteristics	0.5-10000Hz, amplitude error: ±10%; phase error 5%
Measuring range	±50g or $490ms^{-2}$
Amplitude linearity	≤1%

Technical indicators of acceleration vibration signal is shown in Table 1.

Table 2. Technical indicators of speed signal extraction capability

Parameter Name	Parameter
Speed pulse range	1-200000Hz, 1-5V or 0-5V level signal output
Supported speed sensor types	Photoelectric encoder, metal etched speed coding tape, reflective tape

Technical indicators of speed signal extraction capability is shown in Table 2.

Technical indicators of data acquisition is shown in Table 3.

Table 3. Technical indicators of data acquisition

Parameter Name	Parameter
Number of channels	4 channels (synchronous acquisition, BNC connection)
Amplitude quantization accuracy	24bit
Analog input range	±10V, ±1.25V, support IEPE (ICP/CCLD) acceleration sensor input coupling DC/AC IEPE 4mA
Data interface	Support Ethernet cascading
Communication interface	RESTful API, Streaming SDK, Modbus TCP

5.1.4. Technical Advancement

The edge monitoring device is deployed on the wind turbine side, an application platform integrating network communication, specific computing tasks and local data storage. The edge device for shaft misalignment completes monitoring, analysis, early warning, diagnosis and other functions nearby, producing faster responses and meeting the application requirements of wind power equipment condition monitoring, real-time calculation, intelligent analysis, etc. Its advancement is mainly reflected in the following three aspects:

(1) Server-side functions

Manage edge monitoring nodes and their authorized expansion;

Data aggregation and management of edge devices, query time of 10^6 rows of data ≤5 seconds;

Maintain algorithm functions of edge nodes, and can push algorithms or update algorithm parameters to edge devices;

Server-side data processing and analysis, supporting computing load required for complex algorithm analysis.

(2) General functions of edge monitoring devices

Data acquisition and channel configuration, supporting analog data type selection, sampling rate configuration, channel selection;

Local data storage and forwarding of edge monitoring devices, supporting customized storage and forwarding strategies;

The data volume generated by the edge monitoring device in 1 second is:

$$S_s = N_{vib}^{(i)} \times Sv_p \times fv_s + N_r^{(i)} \times fr_s \times Sr_p \quad (1)$$

Where,

S_s - Data volume generated by the edge monitoring device in 1 second, unit (kB, kiloByte);

Sv_p - Data volume of one vibration signal sampling point of the edge monitoring device, unit (kB, kiloByte);

Sr_p - Data volume of one speed signal sampling point of the edge monitoring device, unit (kB, kiloByte);

$N_{vib}^{(i)}$ - Number of vibration signal acquisition channels of the edge monitoring device, $i \in 1,2,3,4$;

$N_r^{(i)}$ - Number of speed signal acquisition channels of the edge monitoring device, $i = 1$;

fv_s - Sampling frequency of vibration measuring points, unit (Hz);

fr_s - Sampling frequency of speed measuring points, unit (Hz).

The edge monitoring device can automatically calculate the data storage duration according to the parameters set by the user. The server creates a scheduled task and pushes the scheduled task strategy for data upload to the edge side.

Customize Web-Api application program interfaces and data interfaces for server invocation or authorized client invocation;

Data visualization, supporting dynamic display of 2D and 3D waveforms;

Special analysis algorithms can be pushed to the edge side remotely, and edge nodes are embedded with Python interpreters, which can directly run algorithm scripts.

On-site networking with edge devices via RJ45 network cables to export data or perform function maintenance, data can be exported to Excel, CSV, Text and other formats.

(3) Special functions of misalignment edge monitoring devices

Pretreatment of vibration signals to remove DC offset;

Calculation of typical characteristic values of vibration signals, such as mean value, variance, effective value, kurtosis, etc.;

Vibration signal spectrum and power spectrum, supporting switching between ordinary coordinates and logarithmic coordinates, maximum spectrum resolution of 0.25Hz, maximum analysis bandwidth of 64kHz. Higher resolution frequency can extract finer frequency analysis and avoid reducing the frequency correlation of fault characteristics due to frequency errors.

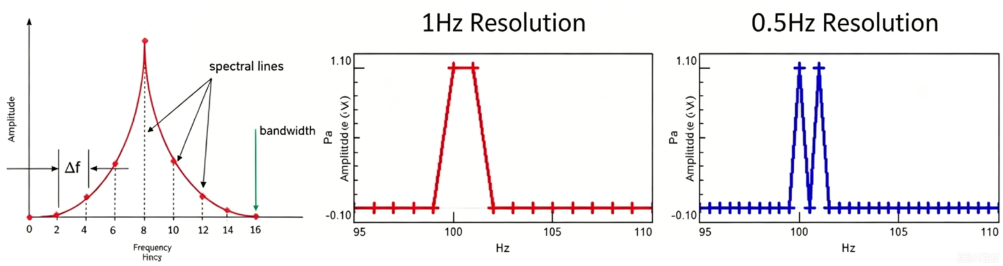

Figure 8. Comparison of spectrum resolution

Comparison of spectrum resolution is shown in Figure 8.

5.1.5. Technical Function Advantages

Aiming at the demand of on-line vibration monitoring of the main drive system of wind turbines, this scheme proposes to develop an edge device for shaft misalignment monitoring. The device can be flexibly deployed in the measured wind turbine to realize real-time monitoring or transmit real-time waveforms and calculation results back to the server when the network environment permits, realizing collaborative computing and analysis between edge nodes and the server. The scheme has expandable equipment structure, flexible deployment and operation, and can collect original waveforms for monitoring in real time. It can adapt to different types of units or application scenarios through algorithm push from the server. Specifically, the edge monitoring device proposed in this scheme has the following advantages:

(1) Reliability: High-performance data acquisition devices ensure high data quality, and the data acquisition module can realize high-speed and high-precision real-time sampling, providing reliable data for subsequent analysis;

(2) Openness: Edge devices can be expanded and deployed, and data interfaces are encapsulated in accordance with general data specifications, improving data transparency and making data easy to invoke and utilize;

(3) Flexibility: Edge monitoring devices have data processing and computing capabilities, and can conduct on-site analysis of original data through server-side algorithm push;

(4) Real-time performance: Edge devices can conduct full-time real-time monitoring and analysis during unit operation, complete analysis of original data, reduce data pressure of real-time communication, and realize synchronous online interaction between edge nodes and servers;

(5) Security: Edge devices can flexibly configure functional algorithms according to different monitoring tasks, and perform multiple monitoring tasks without increasing hardware costs through server push or edge import;

(6) Applicability of in-depth data fusion: Make full use of the angle information of speed measuring devices and time-domain vibration information to provide phase-frequency characteristics, and realize order analysis through angular domain resampling under variable speed conditions;

(7) Transferability of common fault diagnosis models: After cluster deployment of edge monitoring devices, fault characteristics of common equipment faults can be summarized, and fault diagnosis methods can be migrated and applied to other units. Each edge node effectively diagnoses equipment faults, which can be used as a prior probability for fault diagnosis of other units, forming an effective diagnosis case library.

5.2. Problems to Be Solved

(1) Solve the problem of accurate signal perception under complex working conditions: High-precision multi-channel vibration sensor arrays and adaptive anti-interference modules realize broadband and high-resolution signal collection of faults such as gearbox cracks and bearing wear, reducing the missed detection rate in extreme environments.

(2) Solve the problem of invalid fault diagnosis under variable speed conditions: Angular domain resampling algorithm based on instantaneous speed tracking, fused with deep learning feature decoupling model, breaks through the frequency ambiguity bottleneck of traditional spectrum analysis, improves the recognition accuracy of compound faults of planetary gear systems, and supports speed fluctuation conditions.

(3) Solve the problems of closed monitoring system and cross-platform compatibility: Open B/S architecture cloud platform, integrated with Modbus TCP/OPC UA multi-protocol interfaces, shortening cross-model adaptation time and compatible with mainstream models.

(4) Solve the bottleneck of massive data storage and value: Intelligent hierarchical storage strategy and digital twin compression technology reduce data storage capacity, improve the efficiency of key fault feature extraction, and reduce wind farm operation and maintenance costs.

5.3. Expected Achievements

(1) Design a complete technical scheme of wind power intelligent monitoring system;

(2) Develop an engineering prototype of wind power monitoring system and complete wind farm verification;

(3) Apply for 1-2 invention patents or publish 1-2 core journal papers.

6. Conclusions

This project has successfully developed a fully functional edge device for wind turbine condition monitoring, covering comprehensive research areas such as high-precision synchronized signal acquisition, feature extraction under variable-speed conditions, and edge-based collaborative control. The research findings effectively address the challenges of precise signal sensing and system robustness in complex environments. Through field validation at the Huaneng Zhanhua Wind Farm, the system achieved high-precision identification and rapid early warning for typical faults such as misalignment. Although the project has achieved significant milestones, certain limitations remain. For instance, component selection for the current second-generation commercial prototype is constrained by cost, and there is room for improvement in signal reconstruction accuracy under extremely low-speed operating conditions. Future research will focus on introducing digital twin data compression technology to further alleviate storage bottlenecks, and on deeply exploring the identification of common fault patterns based on transfer learning to enhance the diagnostic model's generalization capabilities and intelligence across different turbine models.

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