Renewable Energy and Power Quality Journal
https://repqj.com/index.php/repqj/index
RE&PQJ, Vol. 23, No. 3, 2025

Energy Self-powered Technology in Wind Turbine Tower Bolt Health Monitoring

Wuwen Gao, Cheng Chen, Zhishen Chu, Manhong Jin, Panpan Wang, Zhi Duan*

Ningxia Datang International Hongsipu New Energy Co., LTD., Hongsipu District, Wuzhong City, 751900, China
*Corresponding author email: 18169015989@163.com

Abstract. In wind turbine tower (WTT) bolt health monitoring, traditional energy harvesting devices have low efficiency, insufficient energy conversion efficiency, high energy consumption of monitoring systems, and insufficient system integration and optimization. This paper proposed a new energy self-powered technology to achieve long-term and continuous health monitoring of WTT. It designed an efficient energy harvesting device that used natural energy such as wind turbine tower vibration and temperature change to achieve energy harvesting, optimized materials and structures, improved energy harvesting efficiency, and ensured a long-term stable supply of energy sources. The paper used an efficient energy conversion module to convert the collected mechanical energy and thermal energy into electrical energy, and uses high-capacity energy storage devices for storage, so that the system can operate stably without an external power supply. Energy self-power supply technology can be effectively integrated with the health monitoring system, and low-power sensors and wireless data transmission modules can be designed to reduce the system's overall energy consumption and ensure the real-time collection and transmission of health monitoring data. Intelligent scheduling algorithms optimize energy usage strategies so that energy resources can be reasonably allocated, avoiding excessive consumption of limited energy by the system and realizing long-term stable operation of the WTT monitoring system. The experimental results show that the energy conversion rate of the designed energy harvesting device is 81.7% at a frequency of 100Hz and 79.4% at a high temperature of 100°C, showing obvious advantages in efficiency under vibration frequency and temperature changes. The power consumption of the wireless data transmission module of the self-powered system increases from 15 kW in 6 hours to 22 kW in 24 hours, and the power consumption of the energy management module increases from 12 kW to 18 kW. The power consumption remains low, which is suitable for long-term monitoring tasks.

Key words. Wind Turbine Tower, Bolt Health Monitoring, Energy Self-Powered Technology, Energy Harvesting Device, Intelligent Scheduling Algorithm

1. Introduction

Health monitoring of wind turbine tower (WTT) bolts is crucial to the stability and safety of wind power generation systems because bolts are key components connecting wind turbines to other components, and their health status directly affects the normal operation of wind turbines [1,2]. However, traditional monitoring systems face many challenges, especially regarding energy supply and system integration. Existing monitoring technologies rely on external power supplies or frequent battery replacement, increasing operation and maintenance costs and limiting the feasibility of remote and long-term monitoring. Since wind turbines are located at high altitudes or in remote areas, it is very difficult to obtain external power supplies. At the same time, environmental factors such as vibration and temperature differences provide potential opportunities for energy collection, but existing equipment has significant deficiencies in energy collection and conversion efficiency. To achieve long-term and stable monitoring, problems such as unstable energy supply, poor system integration, and low energy conversion efficiency must be solved [3,4].

WTT health monitoring systems face many challenges in traditional applications. Existing systems rely on external power supplies, affecting the system's stability by the external power supply, and remote and long-term monitoring cannot be achieved [5,6]. Wind turbine towers are located at high altitudes or in inaccessible areas, and external power supply is difficult to obtain [7,8]. Traditional monitoring methods are battery-powered, and battery replacement and maintenance are frequent, which, to a certain extent, increases the operation and maintenance cost and complexity of the system [9,10]. The energy harvesting devices on the market are inefficient, and the energy conversion rate cannot meet the needs of efficient monitoring. The environmental factors of WTT are complex. Vibration and temperature changes can provide the potential for energy harvesting, but the existing equipment has low efficiency in collecting and converting these energy sources [11,12] and cannot provide sufficient power support for long-term monitoring. Traditional energy conversion modules do not fully utilize natural energy, such as temperature differences and vibrations, and cannot guarantee stable operation of the system without an external power supply [13,14]. Regarding system integration, existing technologies lack effective integration of different functional modules. The power consumption of various devices, such as sensors and wireless transmission modules, is high, and low power consumption and long-term continuous operation cannot be achieved [15,16]. The power consumption of sensors limits the frequency of data collection and transmission to a certain extent, and the real-time and accuracy of monitoring data are affected. These systems have significant problems in energy collection and conversion efficiency, energy supply stability, and system integration optimization [17,18]. Traditional monitoring systems lack intelligent scheduling mechanisms and cannot reasonably allocate limited energy resources according to real-time energy demand. The system may suffer from excessive consumption or energy waste during use. These problems are prominent in complex environments and also limit the widespread application and effectiveness of WTT bolt health monitoring systems [19,20]. The traditional WTT bolt health monitoring system has severe technical bottlenecks in energy self-power supply, system integration, energy management, etc., and a more efficient, stable, and durable energy supply solution is needed to meet the needs of long-term and stable monitoring of WTT.

This paper designs and implements a new energy self-power supply technology to support long-term health monitoring of WTT bolts. The existing monitoring system faces problems such as unstable energy supply, low efficiency, and low system integration. The study adopts innovative energy harvesting and conversion technology, explores utilizing natural energy such as WTT vibration and temperature difference, designs efficient energy harvesting devices, improves energy conversion efficiency, and provides continuous and stable power support for the monitoring system. It can reduce the system’s energy consumption, allowing it to run stably for a long time without an external power supply. It uses low-power sensors and wireless data transmission modules to reduce the power demand of each module in the traditional system and combines high-capacity energy storage devices to achieve efficient storage and use of energy. It can design intelligent scheduling algorithms to allocate the energy resources of the system reasonably, avoid excessive consumption of limited energy, and ensure the efficient operation of the monitoring system. This research aims to build an efficient, stable, and low-power WTT bolt health monitoring system to overcome the limitations of existing technologies in energy supply, system integration, and data transmission. This can achieve continuous monitoring of WTT bolts, ensure the safe operation of wind turbines, and provide a technical solution that can be used as a reference for similar applications.

The main contributions of this paper are as follows:

1) Innovative self-powered technology: this paper proposes a new energy self-powered technology that realizes the long-term stable operation of the WTT bolt health monitoring system by utilizing natural energy such as vibration and temperature difference of WTT for energy collection and conversion.

2) Efficient energy collection and conversion design: this paper designs an efficient energy collection device that can effectively extract energy from the vibration and temperature difference of wind turbine towers and improves the energy collection efficiency by optimizing materials and structures.

3) Intelligent scheduling algorithm and low-power system integration; by designing an intelligent scheduling algorithm, the energy use strategy of each module in the system is optimized to avoid excessive consumption of limited energy resources and ensure the long-term stable operation of the monitoring system.

The main framework of this paper is as follows: firstly, the introduction emphasizes the importance of bolt health monitoring of WTT. It points out the challenges of current monitoring systems in terms of energy supply. Next, the related work section reviews the research status of related fields. Then, the design principles, methods, system integration, and optimization of the proposed new energy self-powered technology are elaborated in detail, including the structural design and material optimization of energy harvesting equipment, the optimization of energy conversion and storage systems, and the integration of self-powered monitoring systems. Subsequently, the effect of the method is evaluated, including the evaluation of wireless transmission performance, energy conversion efficiency, monitoring system power consumption, and data transmission stability. Finally, the conclusion summarizes the main contributions of this paper, points out the shortcomings of the research, and looks forward to future research directions and application prospects.

2. Related Work

Regarding the optimization research of wind turbine health monitoring systems, the traditional method mainly focuses on energy collection and conversion technology. Some studies have proposed a wind turbine health monitoring system based on vibration energy collection, which successfully provides partial energy support by converting the energy of tower vibration [21,22]. Kaur N used the direct piezoelectric effect to collect energy from wind vibration and environmental structural vibration, focusing on analyzing the performance of lead zirconate titanate patches under different conditions, and used experimental and numerical methods to evaluate the potential of energy harvesting to provide sustainable energy support for low-power electronic devices [23]. However, this method has low energy conversion efficiency and cannot meet the requirements of long-term stable operation. Some studies have used thermoelectric power generation technology to convert the thermal energy of WTT into electrical energy [24,25]; Cao H proposed a hybrid wind energy collection system that integrates piezoelectric and electromagnetic mechanisms to use canyon side winds to power low-power sensors for bridge health monitoring. The system has high energy conversion performance and mechanical stability at low wind speeds, providing reliable power support for self-powered sensor systems [26]. This method has made some progress in energy collection, but the sustainability of the system's energy supply is still insufficient and highly dependent on environmental conditions. The energy collection and conversion technology in existing research has not yet reached the ideal level of high efficiency, low energy consumption, and long-term stable operation and faces a sizeable technical bottleneck.

Regarding the energy supply problem, recent research has attempted to improve the comprehensive performance of energy collection and monitoring systems through a variety of innovative means. Some scholars have proposed a hybrid energy harvesting method that combines mechanical energy and thermal energy for wind turbine monitoring systems, which has improved the energy conversion efficiency of the system to a certain extent [27,28]. Prasad R proposed a coordinated frequency regulation control mechanism that combines modified pitch angle control and tuned rotor speed control to optimize the frequency regulation performance of wind farms and reduce mechanical stress. This method can effectively improve the response capability under constant and variable wind speeds, and real-time simulation has verified its robustness and superiority [29]. Hybrid energy harvesting systems still face challenges such as unstable energy collection and insufficient system optimization when facing complex environmental changes. Some studies have adopted improved material design to enable energy conversion modules to maintain a high energy conversion rate in low-temperature environments and have made some progress. However, these methods still lack system integration and low-power sensor design [30,31]. This paper designs an efficient energy harvesting device, combined with an intelligent scheduling algorithm and a low-power sensor, which can effectively overcome the shortcomings of existing technologies in energy collection, system stability, and integrated optimization and provide a new solution for WTT bolt health monitoring.

Of course, ensuring data security is also an essential task during the data transmission process. Using encryption and steganography methods to achieve data security on insecure and open networks (such as the Internet) can improve data communication security. Varghese F proposed a comparison method using several encryption algorithms, considering several factors such as block size, key size, encryption speed, memory usage, and security level [32]. Wei H introduced an AI-enhanced anonymous traffic filtering framework with terminal anonymization. The framework uses the Inception-SelfAttBiGRU model to filter malicious traffic. It includes a credibility-based filtering mechanism before the module to reduce network load and improve the system efficiency of these consumer electronic products [33]. Qamar S proposed a new method for secure cloud data transmission and enhanced routing through hybrid machine learning technology [34]. Zhang H started from idle roadside units and studied how to stimulate roadside units to transmit interference power to interfere with eavesdroppers, thereby efficiently and economically improving the security performance of mobile user data transmission [35].

3. Methods

In the bolt health monitoring of WTT, the physical principles of flow quality assessment involve the efficiency of energy collection, conversion, storage, and distribution. First, mechanical vibration and temperature differences provide the source for energy collection. The energy conversion device matches the vibration of the tower body through the resonant frequency to maximize the energy collection efficiency. In contrast, the thermal energy is converted into electrical energy through the thermoelectric converter using the temperature difference. Next, the collected energy is converted into electrical energy through the high-efficiency conversion module and stored in a large-capacity energy storage device. The key to flow quality is to reduce the loss during energy conversion and storage to ensure that the monitoring system can operate continuously and stably. Finally, the intelligent scheduling algorithm optimizes energy distribution. It avoids excessive consumption so that the system can reasonably allocate energy according to real-time needs and maintain low power consumption and long-term stable monitoring functions. These factors together determine the energy flow quality of the entire system and ensure that the self-powered monitoring system can operate efficiently and stably.

A. Design of Energy Harvesting Device

This paper designs an efficient energy harvesting device that uses natural energy, such as WTT vibration and temperature change, to achieve energy harvesting. By optimizing materials and structures, the energy harvesting efficiency is improved to ensure a long-term stable supply of energy sources.

1) Structural Design of Energy Harvesting Device

This study designs an efficient energy harvesting device that integrates vibration energy and temperature energy to improve the energy harvesting efficiency of the WTT bolt health monitoring system. The structure of the device uses a combination of multiple natural energy collection technologies to maximize the energy acquisition rate. The characteristics of WTT vibration are analyzed, and piezoelectric materials and electromagnetic induction devices suitable for the frequency range are selected to convert vibration energy into electrical energy effectively. The device structure uses a multi-layer material stacking method to optimize the vibration characteristics of different parts of the WTT locally so that the energy harvesting device can achieve a high energy conversion rate under various working conditions.

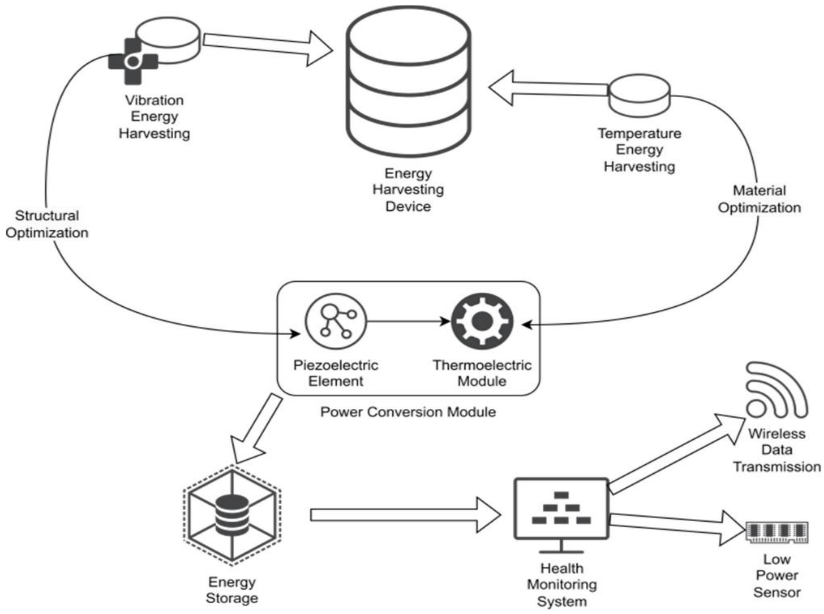

Figure 1. Working principle and structure of energy harvesting device.

The energy harvesting of the WTT bolt health monitoring system's working principle and structure is shown in Figure 1. The system collects natural energy through two methods: the vibration energy harvesting module and the temperature difference energy harvesting module. It uses piezoelectric elements and thermoelectric modules to convert mechanical vibration and temperature difference into electrical energy. The converted electrical energy is processed by an efficient energy conversion module and stored in a high-capacity energy storage device to ensure the system's stable operation when there is no external power supply. The entire energy harvesting device is tightly integrated with the health monitoring system, using low-power sensors to collect the WTT bolts' status data and using a wireless data transmission module to transmit it to the remote platform in real time. Structural optimization and material optimization improve the collection efficiency of vibration energy and temperature difference energy, respectively, ensuring efficient energy utilization of the system; the system uses intelligent scheduling algorithms to reasonably allocate energy resources, ensure long-term stable energy supply, and achieve real-time and reliability of health monitoring.

The acquisition of vibration energy mainly relies on the superposition effect of piezoelectric elements. Optimizing piezoelectric elements' performance requires a special shape design, using bending and multi-frequency coupling technology [36,37] to ensure stable electrical output within a wide frequency band. The vibration energy conversion formula is as follows:

$$P_{\text{vibration}} = \sum_{i=1}^{n} \frac{1}{2} C_i \left(\frac{\mathrm{d}V_i}{\mathrm{d}t} \right)^2 \quad (1)$$

$P_{\text{vibration}}$ is the power converted by the piezoelectric element, C_i is the capacitance of the i th piezoelectric element, and $\frac{\mathrm{d}V_i}{\mathrm{d}t}$ is the voltage change rate of the i th element. The system stability and energy collection capability are improved by combining multiple elements in series and parallel. For the temperature change of WTT, the research and design of an energy harvesting module based on the thermoelectric effect converts temperature difference into electrical energy; the thermoelectric module is composed of thermocouples of two different materials, and the contact interface and cooling system are optimized so that the temperature difference can continuously and stably generate voltage during long-term operation. The conversion formula of thermoelectric energy harvesting is:

$$P_{\text{thermal}} = \alpha \cdot \Delta T \cdot A \cdot \sigma \quad (2)$$

P_{thermal} represents the output power of the thermoelectric module, α is the thermoelectric potential of the thermoelectric material, ΔT is the temperature difference between the two ends, A is the effective area of the thermocouple, and σ is the electrical conductivity of the thermoelectric material. The optimized selection of materials and structural improvements have improved the energy collection efficiency of the thermoelectric module under low-temperature differences, allowing the energy generated by WTT vibration and temperature changes to supply power to the health monitoring system stably. The thermal energy collection module's material property is shown in Table 1.

Table 1. Material properties of thermal energy collection module.

Module Layer	Thermal Conductivity (W/m·K)	Thickness (mm)	Primary Function
Thermal Conduction Layer	256	0.8	Enhances heat transfer efficiency
Thermoelectric Conversion Layer	193	1	Converts temperature gradient into electricity
Insulation Layer	0.02	5	Reduces heat loss

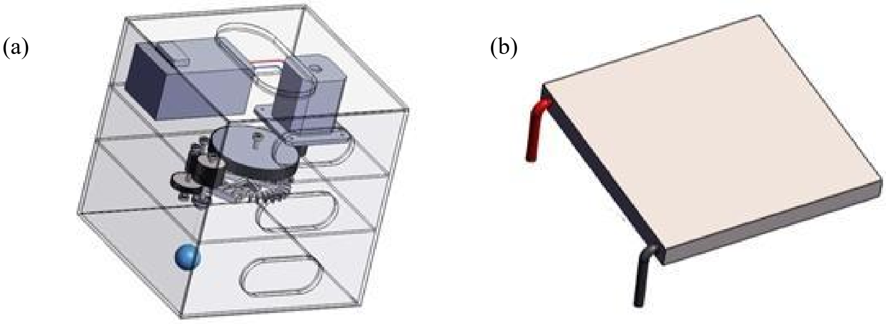

Figure 2. Energy harvesting module. (a) vibration energy harvesting module; (b) temperature difference energy harvesting module.

Figure 2 shows the energy harvesting module. The size of the vibration energy harvesting module is 12cm x 12cm x 16 cm. It is suitable for installation in the parts where the wind turbine tower vibrates frequently. The module uses piezoelectric materials or electromagnetic induction principles to convert the low-frequency vibration generated by the wind turbine tower into electrical energy. The output power is usually between 10 W and 50 W, depending on the vibration amplitude and frequency. The module is suitable for environments with wind speeds of 3 m/s to 12 m/s and can stably collect low-frequency vibration energy. The size of the temperature difference energy harvesting module is 8cm x 8cm x 1cm. It uses the temperature difference inside and outside the wind turbine tower for energy conversion. The output power is between 50 W and 100 W, depending on the size of the temperature difference and the efficiency of the thermoelectric material. The module is suitable for environments with a temperature difference range of 20°C to 100°C, can continuously provide stable electricity, and performs well in areas with large temperature fluctuations.

2) *Material and Structure Optimization*

The study optimized material selection and structural design to improve the energy harvesting device's overall efficiency and long-term stability. Through comparative analysis of the performance of various materials, alloy materials with higher specific energy were selected for the frame and key components of the energy harvesting device. The selection of materials considers conductivity and weather resistance and focuses on its stability under long-term operation, mainly reliability in high vibration and temperature fluctuation environments. The study also adopted an asymmetric material layout to improve the energy collection efficiency of the overall device, focusing on enhancing the energy collection capabilities of those areas with higher vibration intensity and improving the system's energy output under various working conditions.

Regarding structural optimization, a lightweight and compact energy harvesting unit was designed to meet the WTT working environment. A refined design was adopted to reduce the weight and volume of the device and ensure effective coordination between the various harvesting modules. A simulation method based on finite element analysis was used here to comprehensively optimize the device's vibration characteristics and stress conditions to maximize the energy harvesting efficiency. The piezoelectric elements and thermoelectric modules in the device are fixed with a specific mechanical structure, which can effectively absorb external vibrations and temperature changes without affecting the normal operation of the tower; the device with an optimized structure can effectively avoid the problem of energy collection efficiency decline caused by material fatigue or device aging.

The optimized energy harvesting device can achieve stability during long-term operation through material selection and structural design in the multi-energy source integrated design. Given the energy demand of the WTT bolt health monitoring system, the following formula is used to describe the matching of the system power demand and the energy harvesting device:

$$P_{total} = P_{vibration} + P_{thermal} + P_{other} \quad (3)$$

P_{total} is the total power demand, $P_{vibration}$ is the vibration energy harvesting power, $P_{thermal}$ is the thermal energy harvesting power, and P_{other} is the power of other potential energy harvesting sources. The system integration optimization of the device allows the energy harvesting device to maintain a high power output under different working conditions of WTT, ensuring a long-term and stable energy supply.

The optimization of the above material selection and structural design ultimately realizes an energy harvesting device that can work efficiently, long-term, and stably, providing reliable self-powered support for the WTT bolt health monitoring system.

Table 2. Collection of material properties of energy harvesting device.

Material Type	Elastic Modulus (GPa)	Density (kg/m³)	Thermal Conductivity (W/m·K)	Main Application Area
Aluminum Alloy	70	2700	237	Vibration harvester body
Stainless Steel	200	7850	16	Fixing structure
Carbon Fiber Composites	150	1800	5	Vibration-enhancing film
Thermally Conductive Polymer	3	1200	289	Thermal energy conversion module
Titanium Alloy	110	4500	21	High-strength frame
High-Temperature Alloy	180	8200	22	Thermal energy harvesting under extreme conditions

Table 2 lists the materials used in the WTT bolt health monitoring system and their key physical parameters, including elastic modulus, density, and thermal conductivity. The choice of materials is crucial for the design of energy harvesting devices. Table 2 shows aluminum alloy, stainless steel, carbon fiber composite materials, etc. They are used in vibration pickups, fixed structures, and vibration enhancement films, respectively, to enable the system to operate stably in different environments. Titanium alloys and high-temperature alloys can also be used as alternative materials. They have high strength and high-temperature resistance, are suitable for extreme working conditions, and can improve energy collection efficiency and system reliability. A reasonable selection of materials can effectively improve the performance of energy collection devices and ensure a long-term stable energy supply.

B. Energy Conversion and Storage System Optimization

By using efficient energy conversion modules, the collected mechanical and thermal energies are converted into electrical energy, and stored using high-capacity energy storage devices, the system can operate stably without an external power supply, meeting the long-term needs of WTT bolt health monitoring.

1) Energy Conversion Module Optimization

The study adopted an efficient energy conversion module to improve the efficiency of the energy collection system, converting the mechanical energy and thermal energy collected by WTT into electrical energy. For the conversion of mechanical energy, an electromagnetic induction energy conversion scheme was selected; this scheme optimizes the shape and material of the coil, reduces resistance loss, increases the magnetic field strength and relative movement speed, and improves the output of the induced voltage. The device introduces magnetic fluid damping technology to further improve conversion efficiency, reduce system energy loss, and increase the effective utilization of the magnetic field.

In actual energy conversion, the following conversion efficiency calculation formula is set to ensure the efficient operation of the electromagnetic induction module:

$$P_{electromagnetic} = k \cdot \frac{B^2 \cdot A \cdot v^3}{R} \quad (4)$$

$P_{electromagnetic}$ represents the power converted by electromagnetic induction, k is a constant, B is the magnetic field strength, v is the relative speed, and R is the resistance. The layout design of the magnetic field and coil is optimized to improve the power output of the electromagnetic induction module and can more efficiently convert mechanical energy into electrical energy.

The conversion of thermal energy uses thermoelectric modules for temperature difference conversion. Considering the environmental changes monitored by the WTT bolt, the working efficiency of the thermoelectric module is greatly affected by the temperature difference, material properties, and contact surface. To optimize the performance of the thermoelectric module, alloy materials with a high thermoelectric effect are selected, and the microstructure of the thermocouple contact surface is optimized to reduce thermal resistance and increase current output. Based on the optimized thermoelectric module, materials with higher thermoelectric potential and optimized structural design are selected to maximize the voltage output generated by the temperature difference and improve the overall conversion efficiency of the system.

2) Design and Optimization of Energy Storage System

A high-capacity energy storage system is designed to ensure the long-term stable operation of the WTT bolt health monitoring system without an external power supply. The energy storage equipment uses a combination of high-energy-density supercapacitors and lithium batteries to meet different power requirements while extending the system's life. An efficient charge and discharge management algorithm is used to optimize the overall performance of the energy storage system, and accurate battery health status estimation is used to extend the battery life and avoid the risk of overcharging and over-discharging.

The main advantage of supercapacitors is their fast charging and discharging capabilities. They are used as support devices for high-frequency short-term loads. In the design of energy storage modules, supercapacitors are combined with lithium batteries, and the intelligent battery management system is used to adjust the current output and energy storage strategy. The two energy storage devices complement each other to achieve the best energy storage efficiency. The power calculation formula of the energy storage system is as follows:

$$P_{\text{storage}} = \frac{1}{2} C \cdot V^2 \cdot f \quad (5)$$

P_{storage} is the energy storage system's output power; C is the energy storage device's capacitance; V is the voltage; f is the charge and discharge frequency. The energy storage device can provide stable power support under different environmental conditions by selecting suitable capacitors and optimizing battery management.

The study adopted a parallel mode to connect multiple energy storage units to further improve the stability of the energy storage system and used an energy balance algorithm to achieve energy distribution in each unit, avoiding the degradation of the overall system performance caused by the energy attenuation of individual units. The following formula characterizes the energy attenuation problem of the system during long-term operation:

$$E_{\text{decay}} = E_{\text{initial}} \cdot e^{-\lambda t} \quad (6)$$

E_{decay} is the remaining energy of the energy storage device, E_{initial} is the initial energy, and λ is the attenuation coefficient. The scheduling and management of the energy storage device reduces the speed of energy attenuation, allowing the system to maintain the long-term operation of the WTT bolt monitoring system without an external power supply. The energy storage system measures 20 cm x 20 cm x 10 cm, which is suitable for accommodating high-capacity lithium batteries or supercapacitors, and can effectively support the system to continue working without external power. The battery capacity is between 5000 mAh and 10000 mAh, and the voltage range is 3.7V to 12V, ensuring stable power supply during long-term monitoring tasks.

The design and optimization of the above energy storage system can effectively ensure that the WTT bolt health monitoring system can operate stably and continuously collect monitoring data for a long time without an external power supply. This system optimization solution improves the energy conversion efficiency. It enhances the long-term stability of the energy storage system to meet the needs of the WTT bolt health monitoring system.

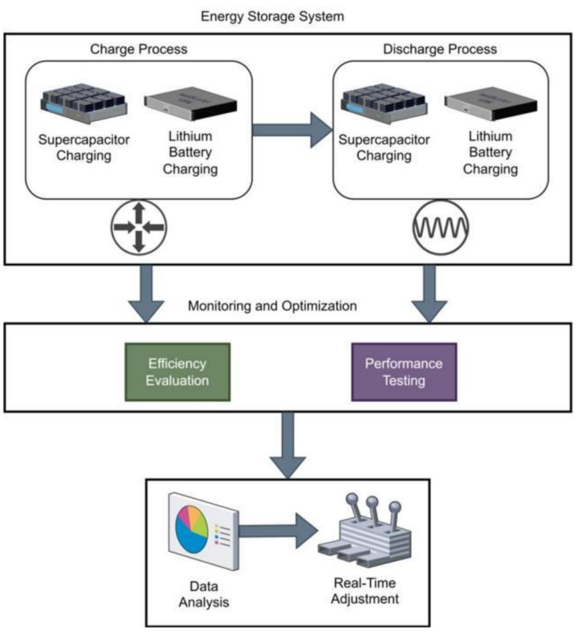

Figure 3. Energy storage system charging and discharging process and the connection between various parts.

Figure 3 details the key links between the energy storage system's charging and discharging process and the connection between various parts. The energy storage system consists of supercapacitors and lithium batteries, and the two have a clear division of labor: supercapacitors are responsible for rapid energy storage and release to cope with the system's high power demand in a short period. Lithium batteries provide long-term continuous power to ensure the stability of system operation; the energy management system schedules the charging and discharging process of supercapacitors and lithium batteries in real time, and uses intelligent algorithms and environmental monitoring data to optimize energy distribution strategies to avoid energy waste or shortages. During the monitoring and optimization phase, the system can conduct real-time evaluation of the charging and discharging efficiency, collect relevant data, and analyze it to stabilize the performance of the energy storage equipment. Based on the results of real-time data analysis, the system can dynamically adjust the operation strategy to further improve the overall efficiency of the energy storage system and provide a long-term and reliable energy guarantee for the WTT bolt health monitoring system.

C. Self-Powered Monitoring System Integration

Energy self-powered technology can be effectively integrated with the health monitoring system, and low-power sensors and wireless data transmission modules can be designed to reduce the system's overall energy consumption and ensure real-time collection and transmission of health monitoring data.

1) Low-Power Sensor Design and Optimization

The research designed a low-power, multifunctional sensor module to reduce the energy consumption of the self-powered monitoring system and ensure high-precision collection of health monitoring data, specifically for health status monitoring of WTT bolts. The sensor is based on piezoelectric effect and strain measurement technology, optimizes the structure and material of the sensing element, and achieves a balance between energy consumption and sensitivity. The core components of the sensor are made using micro-electromechanical system technology, which reduces power consumption and improves signal response speed.

The energy efficiency ratio of low-power sensors is quantified, and the optimization formula for the ratio of sensor power consumption to signal strength is defined as:

$$\eta_{\text{sensor}} = \frac{SNR}{PC_{\text{total}}} \quad (7)$$

η_{sensor} represents the energy efficiency ratio of the sensor, SNR represents the signal-to-noise ratio, and PC_{total} represents the total power consumption of the sensor. After optimizing the design of the sensor circuit, a low-voltage, low-noise amplifier and a dynamic power management circuit are used to maximize the signal strength while reducing power consumption. The study designed an event-triggered sampling mode, which starts the acquisition when a key health status change is detected, reducing unnecessary data acquisition and energy consumption.

A signal enhancement algorithm based on discrete Fourier transform is integrated into the sensor data processing module to filter out environmental noise and improve data accuracy. The calculation formula is as follows:

$$X(k) = \sum_{n=0}^{N-1} x(n) \cdot \mathrm{e}^{-j\frac{2\pi}{N}kn} \quad (8)$$

$X(k)$ is the frequency domain signal component, $x(n)$ is the time domain sampling signal, N is the number of sampling points, and k is the frequency index. The use of an efficient hardware acceleration algorithm to achieve real-time signal processing improves the anti-interference ability of the sensor in complex environments and ensures the reliability of monitoring data.

2) Wireless Data Transmission Module Design and Energy Consumption Optimization

In response to the demand for real-time data transmission in the WTT health monitoring system, a wireless data transmission module based on a low-power vast area network was studied and designed. Dynamic power control technology was used to adjust the transmission power according to the transmission distance and channel conditions, thereby effectively reducing the overall energy consumption of data transmission. The module integrates advanced modulation technology (such as LoRa modulation), which improves data transmission's reliability and anti-interference performance and reduces unnecessary signal transmission. The following formula is defined to analyze the energy efficiency of the transmission module:

$$P_{\text{tx}} = P_{\text{base}} + k \cdot d^2 \quad (9)$$

P_{tx} is the total power consumption of wireless transmission, P_{base} is the essential power consumption, and d is the transmission distance. The detailed analysis and optimization of power consumption distribution allow the adaptive transmission protocol to adjust the transmission distance dynamically and maintain the lowest power consumption at different distances. Combined with the compressed sensing algorithm (CS) [38,39], the data transmission module performs a sparse representation of the monitoring data and only transmits important feature values to reduce communication energy consumption.

To ensure the system's real-time performance, a transmission mechanism based on time synchronization is implemented in the module, which uses low-frequency signals to correct transmission delays. The correction formula is as follows:

$$T_{\text{sync}} = T_{\text{send}} + \Delta t \quad (10)$$

T_{sync} is the time after synchronization, T_{send} is the original sending time, and Δt is the delay correction value. After introducing the synchronization mechanism, the packet loss rate is reduced, and the accuracy of real-time transmission is improved. The transmission module also supports multi-hop routing technology, adapts to the complex network structure under different WTT layouts, and ensures the stable transmission of a wide range of health monitoring data.

The organic combination of low-power sensors and wireless data transmission modules has achieved efficient integration of the WTT self-powered monitoring system; the low-power design ensures the long-term stable operation of the sensor module, and the energy-optimized wireless transmission module effectively reduces the energy consumption of the entire system, meeting the real-time collection and transmission requirements of health monitoring data.

D. System Optimization and Integrated Scheduling

Intelligent scheduling algorithms are used to optimize energy usage strategies to ensure that energy resources are reasonably allocated and to avoid excessive consumption of limited energy by the system.

1) Design of Energy Allocation Optimization Algorithm

The WTT health monitoring system may be interrupted due to excessive energy consumption during long-term operation. A prediction model-based energy allocation optimization algorithm is designed. The algorithm considers the system's real-time energy demand, predicted load changes, and energy collection rate and rationally allocates limited energy resources. By introducing deep reinforcement learning methods, the system can dynamically adjust the sensor's operating mode and data transmission frequency at every moment based on current energy reserves and future energy demand forecasts to optimize energy use.

Here, the system energy efficiency and energy loss functions are defined to evaluate the effect of energy allocation:

$$\varepsilon = \sum_{i=1}^{N} \left(\frac{E_i^{\text{used}}}{E_i^{\text{max}}} \cdot \delta_i \right) \quad (11)$$

E_i^{used} is the actual energy used by the i th node; E_i^{max} is the maximum energy consumption limit of the node; δ_i is the priority coefficient of the node. The optimization goal is to minimize the system's total energy consumption and ensure that all sensors and communication modules can meet the real-time data collection and transmission requirements.

Based on the deep reinforcement learning algorithm, the system uses offline training to learn the energy usage patterns in historical data. It continuously adjusts the strategy in actual operation to optimize energy distribution. Using intelligent scheduling, the system can minimize energy consumption while meeting various monitoring tasks, avoiding unnecessary energy waste caused by unreasonable energy scheduling.

2) Load Prediction and Dynamic Scheduling Optimization

Based on energy allocation, a dynamic scheduling optimization method based on load forecasting is adopted. This method uses time series analysis and machine learning technology based on historical load data to predict the energy demand of each system component in the future. This process uses an autoregressive integral moving average model to predict energy demand and calculate load changes in the future. Based on this, the sensor's working cycle and data collection frequency are dynamically adjusted to avoid wasting energy during low load periods or failure of monitoring tasks due to insufficient energy during peak load periods. The system uses the following formula to predict and schedule the load:

$$\hat{L}_{t+1} = \alpha L_t + \beta L_{t-1} + \gamma \cdot \left(L_t - L_{t-1} \right) \quad (12)$$

$\hat{L}_{t+1}$ represents the predicted value of the load at the next moment. L_t and L_{t-1} represent the load at the current and the previous moments, respectively. Optimizing these parameters can improve the accuracy of load prediction. The dispatching system can automatically reduce the frequency of sensor data collection when the load is low by using the predicted value, reducing the overall power consumption of the system and achieving the purpose of saving energy.

Combined with the system energy status and task priority, the scheduling system optimizes the execution order of data collection, transmission, and storage tasks in each cycle. The execution order and priority of tasks can be adjusted dynamically to avoid delays in key tasks of the system when energy is tight, ensuring the real-time nature of data and the long-term stable operation of the system. Based on the task priority and energy consumption model, the system can optimize the task scheduling strategy according to the following formula in each scheduling cycle:

$$T_{\text{opt}} = \arg\min\left(\sum_{j=1}^{S}\left(P_j \cdot \delta_j\right)\right) \quad (13)$$

T_{opt} is the optimized task scheduling sequence. P_j is the energy consumption of task j. δ_j is the task's priority. S is the total number of tasks. This scheduling algorithm enables the system to effectively avoid uneven distribution of energy resources and achieve optimal energy use and task scheduling.

With load prediction and dynamic scheduling optimization strategy, the system can reasonably allocate limited energy resources under various operating environments, adjust the operating strategy when facing sudden load changes, and ensure the long-term stable operation of the WTT bolt health monitoring system. This optimization method improves the system's energy efficiency, extends the working cycle of the self-powered monitoring system, and meets the real-time and high-efficiency requirements of the monitoring task.

In general, this paper designs a new type of energy self-powered technology, which mainly collects energy by utilizing natural energy such as vibration and temperature difference of WTT. The specific methods include: First, an efficient energy collection device is designed to extract mechanical energy and thermal energy from the vibration and temperature difference of the tower body, and the collection efficiency is improved by optimizing materials and structures. Then, an efficient energy conversion module is used to convert the collected mechanical energy and thermal energy into electrical energy, and it is stored through a high-capacity energy storage device to ensure that the system can continue operating without an external power supply. In addition, to reduce energy consumption, the system uses low-power sensors and wireless data transmission modules and optimizes energy distribution through intelligent scheduling algorithms to avoid excessive energy consumption and ensure the long-term stable operation of the system.

4. Method Effect Evaluation

This paper simulates the working conditions of a wind power tower in an experimental environment and uses vibration and temperature change test methods to evaluate the performance of the designed energy harvesting device. Specific tests include measuring the energy conversion efficiency under different frequency and temperature conditions. In addition, the authors also evaluate the power consumption changes of the system during continuous operation through long-term monitoring experiments, such as the power consumption changes of the wireless data transmission module and the energy management module, to verify the system's stability, energy efficiency, and adaptability. Table 3 shows the parameters of the targeted wind turbine.

Table 3. Parameters of the targeted wind turbine.

Parameter	Value	Unit	Description
Rotor Diameter	120	m	Diameter of the rotor, determining the swept area
Rated Power	2.5	MW	The rated output power of the wind turbine
Rated Wind Speed	12	m/s	Wind speed at which the rated power is generated
Starting Wind Speed	3	m/s	Minimum wind speed required to start generating power
Maximum Wind Speed	25	m/s	Maximum design wind speed, beyond which the turbine stops
Operating Temperature	-20~40	°C	Temperature range in which the turbine operates
Weight	250	tons	Total weight of the wind turbine
Tower Height	80	m	Height of the tower, affecting wind capture efficiency
Maximum Rotation Speed	20	rpm	Maximum rotational speed of the blades
Turbine Efficiency	40	%	Efficiency of converting wind energy to mechanical energy
Monitoring System Power Consumption	10	W	Power consumption of the health monitoring system

A. Changes in Wireless Transmission Performance and Energy Management

Figure 4 shows the changes in wireless transmission performance and energy management in the WTT health monitoring system. Figure 4a shows the relationship between wireless transmission and power consumption. The surfaces of different colors reflect the changes in power consumption and show the dynamic trend of power consumption at various distances and data loss rates. As the transmission distance and data loss rate increase, power consumption gradually increases. The system's energy efficiency is significantly affected by the quality of the wireless signal and the transmission distance. Figure 4b focuses on the system's energy management, showing energy collection, energy consumption, and net energy through different colored areas. The net energy is the difference between collection and consumption. As time goes by, energy collection and consumption fluctuate periodically. The fluctuation of energy is affected by WTT vibration and temperature changes. By comparing the collected and consumed energy, the stability and efficiency of the system in the self-powered mode can be intuitively evaluated. Without an external power supply, the system can continue to operate stably.

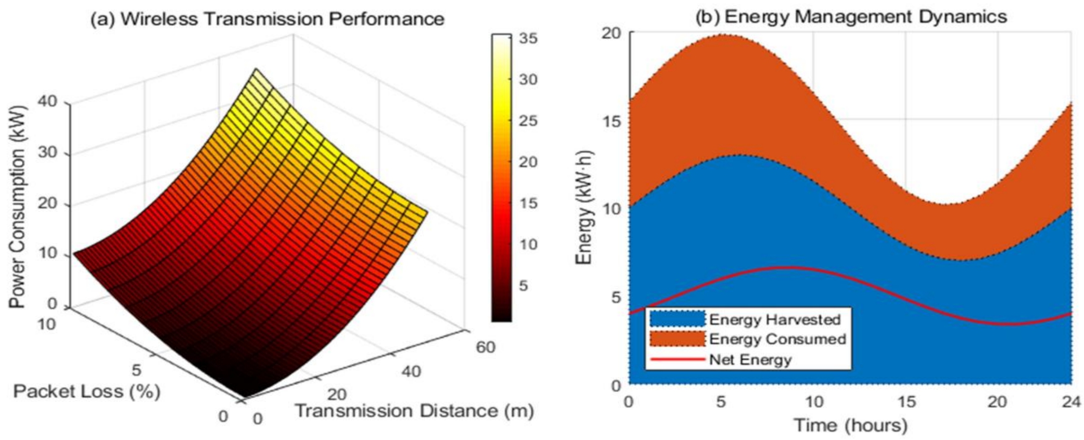

Figure 4. Dynamic changes in wireless transmission performance and energy management.

B. Energy Conversion Efficiency Evaluation

Figure 5 shows the energy demand and various energy collections of the WTT bolt health monitoring system within 24 hours. The energy sources are vibration energy, thermal energy, and other energy, Other energy sources are natural energy sources available in the environment, such as solar energy and wind energy. These energy sources are converted into electrical energy through solar panels and wind power generation devices to provide stable energy support for the system. The power required by the system is provided by these devices, mainly used to drive monitoring sensors, data acquisition modules, wireless communication equipment and other loads. The loads cover temperature and humidity sensors, accelerometers, temperature sensors, data processing units, etc. The power they consume ensures the continuous and stable operation of the system. Vibration energy increases during periods of high energy demand in the system, showing a higher level of energy harvesting, reflecting the positive correlation between WTT vibration intensity and energy harvesting efficiency; the amount of thermal energy collected is also high, and the energy harvesting efficiency is high, reflecting the impact of ambient temperature difference on energy harvesting; other energy sources provide relatively stable additional energy, with a more minor contribution, but give stable support to system operation. The efficient collection of vibration and thermal energy ensures the system's energy supply within 24 hours and effectively meets the energy demand of WTT bolt health monitoring during high-load periods.

The energy conversion efficiency evaluation is carried out under different working conditions, monitoring the system's energy input and output, setting various working conditions, temperature changes, and vibration intensity, and simulating various scenarios in actual operation. It can record the collection of natural energy, such as WTT vibration and temperature changes, monitor the output energy in real time, and ensure that the electric energy generated by the energy conversion module can be accurately obtained.

During the evaluation, high-precision measuring instruments are required to synchronously record the input and output energy and evaluate the response ability and stability of the conversion module based on the energy changes under different working conditions. The optimized energy collection and conversion performance is compared with that of the traditional energy harvesting device under the same conditions, and the adaptability and efficiency under different environmental factors are studied. The evaluation results provide an essential basis for the subsequent optimization design. Under changing environmental conditions, the system can efficiently and stably convert and store energy.

Figure 6 shows different energy harvesting devices' energy conversion efficiency performance under vibration frequency and temperature changes. Figure 6a shows the comparison between vibration frequency and energy conversion efficiency. The energy conversion efficiency of the designed energy harvesting device at different vibration frequencies is significantly better than that of traditional piezoelectric and thermoelectric devices. The efficiency of the designed device increases steadily with the frequency increase, from 74.5% to 81.7%, showing good high-frequency adaptability. The efficiency increase of piezoelectric and thermoelectric devices is relatively small. These two traditional devices have limited energy conversion capabilities under high-frequency vibration and low overall efficiency. The efficiency improvement of the designed device during frequency changes is more significant and is more suitable for the advantages of high-frequency vibration environments. Figure 6b shows the comparison between temperature and energy conversion efficiency. Under the condition of temperature change, the designed device also shows strong energy conversion ability, and its efficiency increases from 75.0% to 79.4%. The designed device can adapt to temperature changes, and its efficiency increases steadily with the increase in temperature; the efficiency of piezoelectric and thermoelectric devices increases more slowly. The changes show that the adaptability of the traditional device under temperature changes is not as good as that of the designed device, and the efficiency improvement is limited. The efficiency of the designed device under vibration frequency and temperature changes show apparent advantages.

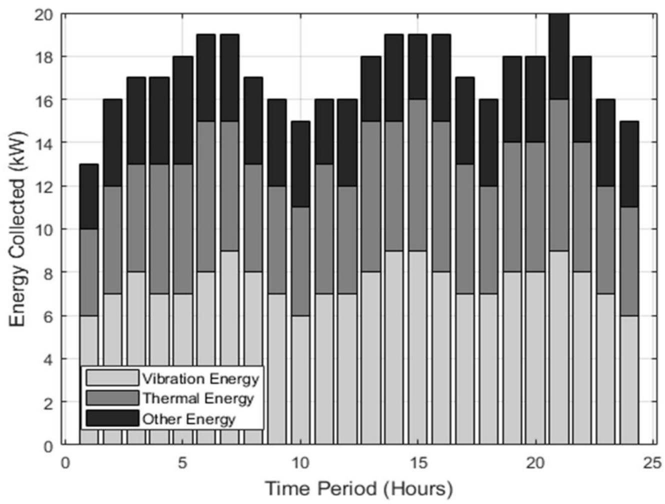

Figure 5. Changes of energy collected from different sources over time.

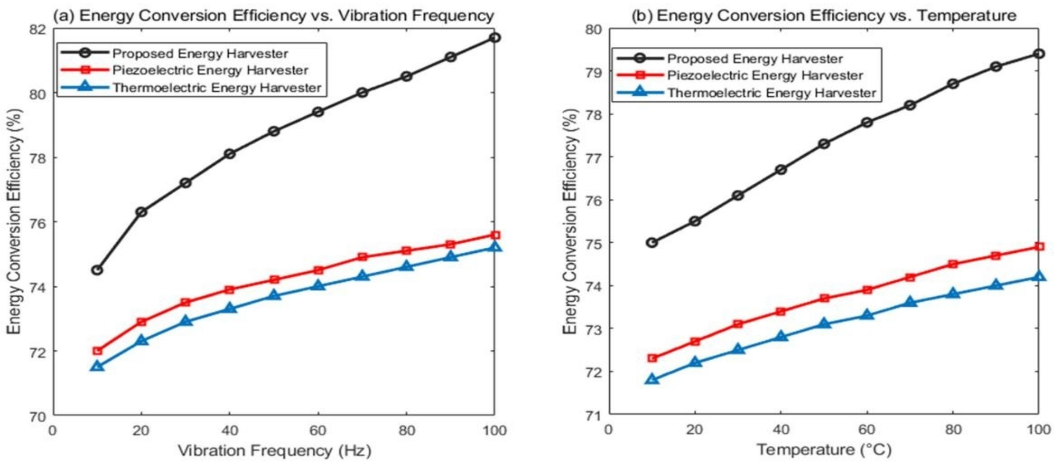

Figure 6. Energy conversion efficiency performance of different energy harvesting devices under vibration frequency and temperature changes.

C. Monitoring System Power Consumption Evaluation

Monitoring system power consumption evaluation requires long-term continuous operation testing to record the actual power consumption of the system in different periods. High-precision power monitoring instruments can be used to track the power consumption of various parts of the system in real time, focusing on the energy consumption performance of the wireless data transmission module and the energy management module.

The power consumption data of the optimized energy self-powered system can be compared with that of the traditional system under the same conditions to clarify the impact of optimization measures on reducing system power consumption. The system's stability in low-power mode can be analyzed, and its power consumption fluctuations during long-term operation can be evaluated to examine whether the system can maintain a continuous and stable working state without exceeding energy resource constraints. This evaluation provides a basis for subsequent adjustments and optimization designs to ensure the system can achieve long-term stable operation under energy-constrained conditions.

Figure 7 shows the power consumption comparison between a self-powered system and a traditional system. The power consumption of energy self-powered system is generally low, and the power consumption shows a certain growth trend over time. The power consumption of the wireless data transmission module of the self-powered system increases from 15 kW in 6 hours to 22 kW in 24 hours. The power consumption of the energy management module increases from 12 kW to 18 kW. These changes show that the power consumption of the energy self-powered system improves over time, but the overall power consumption remains at a low level, which is suitable for long-term monitoring tasks. The power consumption of the traditional system is higher, and the wireless data transmission module increases from 25 kW for 6 hours to 32 kW for 24 hours. The power consumption of the wireless data transmission module increases significantly, showing the high demand of the traditional system in energy consumption under continuous operation. These changes reflect the unsustainability of the energy consumption of the traditional system, and additional power support is needed when facing the challenges of long-term operation. The optimized energy self-powered system performs well in power consumption control, can operate stably, and can successfully complete long-term health monitoring tasks without relying on an external power supply.

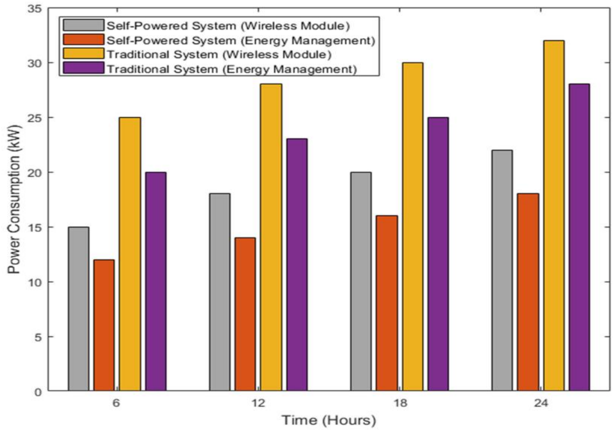

Figure 7. Power consumption comparison between self-powered system and traditional system.

D. Data Transmission Stability Evaluation

In the data transmission stability assessment, different transmission frequencies are set as actual operating conditions to test the transmission performance of the system under various conditions. Special test tools are configured to monitor the sending and receiving of data packets in real time, and record key indicators such as data packet loss rate and transmission delay. The test can be repeated many times to ensure the stability and reliability of the measurement results. The performance of the optimized system is compared with that of the traditional system under the same test conditions to evaluate the effect of the optimization measures on the stability of data transmission. The evaluation provides a practical basis for optimizing the design of the data transmission module to ensure that the monitoring data can be transmitted to the target terminal in a timely and accurate manner.

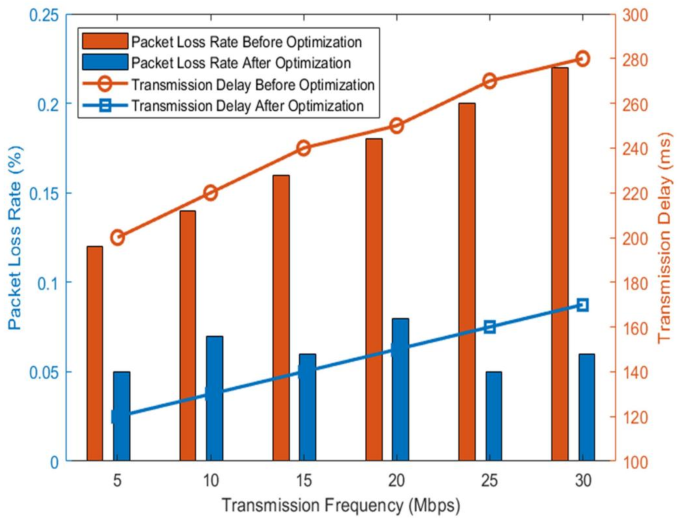

Figure 8. Comparison of packet loss and transmission delay before and after optimization.

Figure 8 compares the packet loss rate and data transmission delay of the system at different data transmission frequencies before and after optimization. The packet loss rate of the optimized system at all frequencies is significantly lower than before optimization, indicating that the optimization measures have effectively improved the stability of the system and the reliability of data transmission. The packet loss rate of the system before optimization gradually increased. In contrast, the packet loss rate of the system after optimization remained at a low level, indicating that the optimized system has stronger adaptability to high-frequency data transmission. The broken line of data transmission delay shows that the delay of the optimized system has increased, but the increase is slight. The optimization measures have improved the system’s stability to a certain extent. In the case of high-frequency transmission, the delay change is more prominent. The optimized system has achieved a good balance between packet loss rate and delay and has strong overall performance and stability.

5. Conclusions

This paper proposes and implements a new energy self-powered technology to support the long-term health monitoring of WTT bolts. The paper achieved an efficient energy collection and long-term stable supply by designing harvesting equipment, such as wind tower vibration and temperature difference for energy collection and conversion, combining with optimizing materials and structures. This technology not only overcomes the limitations of traditional monitoring systems in energy supply, system integration, and data transmission but also effectively reduces the system's overall energy consumption through the design of low-power sensors and wireless data transmission modules. However, this study still has certain shortcomings, such as room for improvement in energy harvesting efficiency and stability verification of the system under complex environments. In future research, more efficient energy conversion mechanisms can be further explored, and system integration can be optimized. The intelligence of energy management strategies also can be improved to enhance the adaptability and durability of the system under different climatic conditions. Meanwhile, more field tests can be carried out to comprehensively evaluate the long-term performance and reliability of the self-powered monitoring system and promote its widespread application in wind power generation.

Acknowledgment

None

Consent to Publish

The manuscript has neither been previously published nor is under consideration by any other journal. The authors have all approved the content of the paper.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Funding

None

Author Contribution

Wuwen Gao, Cheng Chen: Developed and planned the study, performed experiments, and interpreted results. Edited and refined the manuscript with a focus on critical intellectual contributions.

Zhishen Chu, Manhong Jin: Participated in collecting, assessing, and interpreting the date. Made significant contributions to date interpretation and manuscript preparation.

Panpan Wang, Zhi Duan: Provided substantial intellectual input during the drafting and revision of the manuscript.

Conflicts of Interest

The authors declare that they have no financial conflicts of interest.

References

[1] N. Stavridou, E. Koltsakis, C.C. Baniotopoulos. A comparative life-cycle analysis of tall onshore steel wind-turbine towers. Clean Energy, 2020, 4(1), 48-57. DOI: 10.1093/ce/zkz028

[2] Z.J. Han, Z.J. Liu, W. Kang, W. He. Boundary feedback control of a nonhomogeneous wind turbine tower with exogenous disturbances. IEEE Transactions on Automatic Control, 2021, 67(4), 1952-1959. DOI: 10.1109/TAC.2021.3071021

[3] P.G. Hubbard, J. Xu, S.H. Zhang, M. Dejong, L.Q. Luo, et al. Dynamic structural health monitoring of a model wind turbine tower using distributed acoustic sensing (DAS). Journal of Civil Structural Health Monitoring, 2021, 11(3), 833-849. DOI: 10.1007/s13349-021-00483-y

[4] B.D. Lago, L. Flessati, P. Marveggio, P. Martinelli, G. Fraraccio, et al. Experimental tests on shallow foundations of onshore wind turbine towers. Structural Concrete, 2022, 23(5), 2986-3006. DOI: 10.1002/suco.202100655

[5] D. Li, Z. Zhang, X.K. Zhou, Z.Y. Zhang, X.Q. Yang. Cross-wind dynamic response of concrete-filled double-skin wind turbine towers: Theoretical modelling and experimental investigation. Journal of Vibration and Control, 2023, 30(13-14), 2881-2893. DOI: 10.1177/10775463231186708

[6] B.G. Stokke, T. Nygård, U. Falkdalen, H.C. Pedersen, R. May. Effect of tower base painting on willow ptarmigan collision rates with wind turbines. Ecology and Evolution, 2020, 10(12), 5670-5679. DOI: 10.1002/ece3.6307

[7] S.P. Mulders, T.G. Hovgaard, J.D. Grunnet, J.V. Wingerden. Preventing wind turbine tower natural frequency excitation with a quasi-LPV model predictive control scheme. Wind Energy, 2019, 23(3), 627-644. DOI: 10.1002/we.2447

[8] J.L. Chen, J.W. Li, D.W. Wang, Y.Q. Feng. Seismic response analysis of steel–concrete hybrid wind turbine tower. Journal of Vibration and Control, 2021, 28(17-18), 2240-2253. DOI: 10.1177/1077546321100759

[9] K. Dai, H. Huang, Y. Lu, J.Y. Meng, Z.X. Mao, et al. Effects of soil–structure interaction on the design of tuned mass damper to control the seismic response of wind turbine towers with gravity base. Wind Energy, 2021, 24(4), 323-344. DOI: 10.1002/we.2576

[10] X.G. Huang, B.K. Li, X.H. Zhou, Y.H. Wang, J.L. Bai, et al. Computational study of steel–concrete hybrid wind turbine tower seismic performance. Journal of Earthquake Engineering, 2022, 27(10), 2796-2817. DOI: 10.1080/13632469.2022.2121789

[11] S.Z. Li, H. Li, X.H. Zhou, Y.H. Wang, X.H. Li, et al . Damage detection of flange bolts in wind turbine towers using dynamic strain responses. Journal of Civil Structural Health Monitoring, 2022, 13(1), 67-81. DOI: 10.1007/s13349-022-00622-z
[12] K.A. Kapasakalis, I.A. Antoniadis, E.J. Sapountzakis, A.E. Kampitsis. Vibration mitigation of wind turbine towers using negative stiffness absorbers. Journal of Civil Engineering and Construction, 2021, 10(3), 123-139. DOI: 10.32732/jcec.2021.10.3.123
[13] C.Z. Ma, Z. Lu, D.C. Wang, Z.X. Wang. Study on the damping mechanisms of a suspended particle damper attached to a wind turbine tower. Wind and Structures, 2021, 33(1), 103-114. DOI: 10.12989/was.2021.33.1.103
[14] A. Yamaguchi, P.W. Sarli, T. Ishihara. Extreme load estimation of the wind turbine tower during power production. Wind Engineering, 2019, 45(1), 93-106. DOI: 10.1177/0309524X19872766
[15] G. Liu, Z.B. Lei, W. Yang, Y. Li. Mechanism analysis and parameter tuning optimization for wind turbine towers with PS-TMD passive control devices. Engineering Mechanics, 2021, 38(12), 137-146. DOI: 10.6052/j.issn.1000-4750.2020.11.0851
[16] R.F. Zhang, Y.R. Cao, K.S. Dai. Response control of wind turbines with ungrounded tuned mass inerter system (TMIS) under wind loads. Wind and Structures, 2021, 32(6), 573-586. DOI: 10.12989/was.2021.32.6.573
[17] G.D. Cillis, S. Cherubini, O. Semeraro, S. Leonardi, P.D. Palma. POD-based analysis of a wind turbine wake under the influence of tower and nacelle. Wind Energy, 2020, 24(6), 609-633. DOI: 10.1002/we.2592
[18] S.C. Mondal, P.L.C. Marquez, M.O. Tokhi. Analysis of mechanical adhesion climbing robot design for wind tower inspection. Journal of Artificial Intelligence and Technology, 2021, 1(4), 219-227. DOI: 10.37965/jait.2021.0013
[19] R. Wiser, D. Millstein, M. Bolinger, S. Jeong, A. Mills, et al. The hidden value of large-rotor, tall-tower wind turbines in the United States. Wind Engineering, 2021, 45(4), 857-871. DOI: 10.1177/0309524X20933949
[20] M.A. Jaimes, A.D. García-Soto, J.O. Martín del Campo, A. Pozos-Estrada. Probabilistic risk assessment on wind turbine towers subjected to cyclone-induced wind loads. Wind Energy, 2020, 23(3), 528-546. DOI: 10.1002/we.2436
[21] A.M. Masood, K.F. Ullah. Two degree of freedom vibration based electromagnetic energy harvester for bridge health monitoring system. Journal of Intelligent Material Systems and Structures, 2020, 32(5), 516-536. DOI: 10.1177/1045389X20959459
[22] H. Badihi, Y.M. Zhang, B. Jiang, P. Pillay, S. Rakheja. A comprehensive review on signal-based and model-based condition monitoring of wind turbines: Fault diagnosis and lifetime prognosis. Proceedings of the IEEE, 2022, 110(6), 754-806. DOI: 10.1109/JPROC.2022.3171691
[23] N. Kaur, D. Mahesh, S. Singamsetty. An experimental study on piezoelectric energy harvesting from wind and ambient structural vibrations for wireless structural health monitoring. Advances in Structural Engineering, 2019, 23(5), 1010-1023. DOI: 10.1177/136943321988695
[24] H.S. Kim, S.I. Jeong. A Study on the Safety by Thermal Characteristics of Tubular Linear Generator for Bladeless Wind Power Generation System. Journal of Electrical Engineering & Technology, 2024, 19(3), 1965-1972. DOI: 10.1007/s42835-023-01726-2
[25] K.X. Wei, Y. Yang, H.Y. Zuo, D.Q. Zhong. A review on ice detection technology and ice elimination technology for wind turbine. Wind Energy, 2019, 23(3), 433-457. DOI: 10.1002/we.2427
[26] H. Cao, X.P. Wu, H. Wu, Y.J. Pan, D.B. Luo, et al. A hybrid self-powered system based on wind energy harvesting for low-power sensors on canyon bridges. International Journal of Precision Engineering and Manufacturing-Green Technology, 2023, 10(1), 167-192. DOI: 10.1007/s40684-022-00424-0
[27] L.X. Yang, Z.J. Zhang. A conditional convolutional autoencoder-based method for monitoring wind turbine blade breakages. IEEE Transactions on Industrial Informatics, 2020, 17(9), 6390-6398. DOI: 10.1109/TII.2020.3011441
[28] X.C. Liu, J. Du, Z.S. Ye. A condition monitoring and fault isolation system for wind turbine based on SCADA data. IEEE Transactions on Industrial Informatics, 2021, 18(2), 986-995. DOI: 10.1109/TII.2021.3075239
[29] R. Prasad, N.P. Padhy. Synergistic frequency regulation control mechanism for DFIG wind turbines with optimal pitch dynamics. IEEE Transactions on Power Systems, 2020, 35(4), 3181-3191. DOI: 10.1109/TPWRS.2020.2967468
[30] T. Xue, J. Lyu, H. Wang, X. Cai. A complete impedance model of a PMSG-based wind energy conversion system and its effect on the stability analysis of MMC-HVDC connected offshore wind farms. IEEE Transactions on Energy Conversion, 2021, 36(4), 3449-3461. DOI: 10.1109/TEC.2021.3074798
[31] A. Sattar, A. Al-Durra, C. Caruana, M. Debouza, S.M. Muyeen. Testing the performance of battery energy storage in a wind energy conversion system. IEEE Transactions on Industry Applications, 2020, 56(3), 3196-3206. DOI: 10.1109/TIA.2020.2979792
[32] F. Varghese, P. Sasikala. A detailed review based on secure data transmission using cryptography and steganography. Wireless Personal Communications, 2023, 129(4), 2291-2318. DOI: 10.1007/s11277-023-10183-z
[33] H. Wei, J.F. Miao, J.H. Lv, C.M. Chen. Secure and Trustworthy Data Management Mechanism for Dance-Consumer Electronics in AIoT. IEEE Transactions on Consumer Electronics, 2024, 99. DOI: 10.1109/TCE.2024.3471573
[34] S. Qamar, M. Amaan, M.I. Rahman, I. Aqeel, M. Shuaib, et al. Cloud data transmission based on security and improved routing through hybrid machine learning techniques. Soft Computing, 2023, 1-8. DOI: 10.1007/s00500-023-08417-0
[35] H. Zhang, J.B. Xue, X.R. Guan, Z.R. Ma, J.L. Xu. An optimization scheme of data link security transmission based on mobile edge computing. Ad Hoc Networks, 2024, 162, 103556. DOI: 10.1016/j.adhoc.2024.103556
[36] S.H. Tsai, H. Ouyang, J.Y. Chang. A receptance-based method for frequency assignment via coupling of subsystems. Archive of Applied Mechanics, 2020, 90(2), 449-465. DOI: 10.1007/s00419-019-01619-9
[37] Z. Zhang, X.Y. Li, H.L. Pang, H. Komurcugil, Z.Y. Liang, et al. Multiple-frequency resonating compensation for multichannel transmission of wireless power transfer. IEEE Transactions on Power Electronics, 2020, 36(5), 5169-5180. DOI: 10.1109/TPEL.2020.3027916
[38] V.K. Amalladinne, J.F. Chamberland, K.R. Narayanan. A coded compressed sensing scheme for unsourced multiple access. IEEE Transactions on Information Theory, 2020, 66(10), 6509-6533. DOI: 10.1109/TIT.2020.3012948
[39] G. Xu, B.J. Zhang, H.W. Yu, J.L. Chen, M.D. Xing, et al. Sparse synthetic aperture radar imaging from compressed sensing and machine learning: Theories, applications, and trends. IEEE Geoscience and Remote Sensing Magazine, 2022, 10(4), 32-69. DOI: 10.1109/MGRS.2022.321880