Research on Innovative Application of Energy Self-Powering Technology in Health Monitoring of Wind Turbine Tower Bolts

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ABSTRACT To reduce the operation and maintenance losses caused by critical component failures in wind turbines, this study proposes a piezoelectric-electromagnetic multi-source energy self-powering scheme for tower bolt health monitoring, providing an efficient solution for long-term autonomous sensing in intelligent electromechanical systems. Considering the growing demand for low-power electromagnetic energy harvesting and reliable wireless monitoring technologies, the bolt failure mechanism and tower operating environment are systematically analyzed to develop an innovative composite architecture integrating an arc-shaped piezoelectric harvesting unit with a micro electromagnetic energy acquisition module and a low-power energy management system. A three-level validation framework consisting of simulation, laboratory experiments, and engineering deployment is established to evaluate the proposed approach. Experimental results demonstrate that the device achieves an energy conversion efficiency of 28.7% under vibration frequencies of 0.1–5 Hz and continuously powers monitoring nodes for more than 30 days. Field deployment in a northern wind farm enables 72-hour early warning of bolt loosening and reduces the annual maintenance cost of a single turbine by approximately 32,000 yuan. The proposed self-powered monitoring framework provides a compact, long-life, and cost-effective solution for structural health monitoring of critical infrastructure and offers valuable technical references for electromagnetic energy harvesting, intelligent sensing networks, and wireless monitoring applications in advanced engineering systems.

INDEX TERMS wind turbine tower, bolt health monitoring, piezoelectric-electromagnetic energy harvesting, self-powered sensing, electromagnetic monitoring

I. INTRODUCTION

A. RESEARCH BACKGROUND AND SIGNIFICANCE

As traditional fossil energy sources become increasingly depleted, the worldwide development of renewable energy technologies is a critical major issue that must be addressed, particularly to meet the substantial and sustainable resource requirements of global manufacturing operations. Wind power generation has become a new energy technology developed by various countries due to its advantages in cost and environment [1]. As the core load-bearing structure of wind power equipment, the health status of the connecting bolts of the wind turbine tower directly determines the operational safety of the unit [2]. According to the wind turbine accident statistics (1975 to 2020) provided by the Caithness Wind Farm Information Forum, a total of 221 accidents were found, most of which were bolt fractures at the tower flange and bending caused by fatigue crack propagation [3,4]. Bolt failure has the characteristic of concealment: the alternating load generated by the rotation of the impeller makes the bolt bear continuous tensile stress, and there are often no obvious signs from loosening to fracture, making it difficult for traditional manual inspection to give early warning [5]. Existing bolt monitoring technologies rely on cable power supply or battery power supply, which increases the operation and maintenance costs and limits the feasibility of remote and long-term monitoring [6]. The self-powering technology can use environmental energy such as tower vibration and temperature difference to continuously supply power to monitoring nodes, with three advantages: first, it reduces operation and maintenance costs by avoiding frequent battery replacement; second, it has flexible deployment and adapts to narrow high-altitude spaces; third, it has a long system life, which can match the 20-year service cycle of wind turbines [7]. Therefore, researching the innovative application of self-powering technology in bolt health monitoring holds important theoretical and engineering significance not only for improving the intelligent operation and maintenance of wind power but also for enhancing equipment safety across various high-vibration manufacturing environments.

B. RESEARCH STATUS AT HOME AND ABROAD

1) Research Progress of Wind Turbine Tower Bolt Health Monitoring Technology

Bolt health monitoring technology has evolved from offline detection to online monitoring [8]: in the early stage, manual torque wrench re-inspection was adopted, which was low in efficiency and limited in accuracy; existing technologies are mainly based on sensor monitoring, including strain gauges for measuring pre-tightening force and vibration sensors for measuring loosening status [9,10]. The rapid development of artificial intelligence technology has brought significant changes to the field of bolt loosening monitoring. Among many innovative studies, Young-Jin Cha and other researchers first introduced image recognition technology into this field and proposed a detection method based on visual features [11]. Passive wireless monitoring technology has emerged in recent years [12]; sensors are embedded in bolt connections in the form of gaskets without batteries and wiring, and have been applied in wind power [13], rail transit [14] and other scenarios, but this technology relies on external reader excitation and has a limited monitoring distance (usually <5 m).

2) Research Status of Energy Self-Powering Technology in Industrial Scenarios

Industrial self-powering technologies are mainly divided into four categories: piezoelectric, electromagnetic, thermoelectric and multi-energy complementation [15]: Piezoelectric technology realizes power supply through mechanical energy-electric energy conversion. The output power of arc-shaped piezoelectric ceramics in vibration scenarios can reach 5.95 mW, but its output is significantly affected by vibration frequency [16,17]; Electromagnetic technology is based on the principle of electromagnetic induction. After miniaturization design, the output power reaches 5.65 mW under low-frequency vibration, which is suitable for the tower vibration environment [18,19]; Thermoelectric technology uses temperature difference to generate electricity. When the temperature difference between the tower and the environment is 10°C, the output power is about 1 μW, with low energy density [20]. Multi-energy complementation technology has become a research hotspot: scholars from Huazhong Agricultural University developed a triboelectric-electromagnetic hybrid generator (TEHG) to achieve efficient wind energy collection, and the photovoltaic-energy storage dual-mode power supply system has a endurance capacity of 30 days [21]. However, the existing composite devices are relatively large (diameter usually >50 mm) and cannot be adapted to the bolt installation space.

3) Application Bottlenecks of Self-Powering Technology in Bolt Monitoring Field

Although self-powering technology has developed rapidly, its application in bolt monitoring scenarios still faces three major bottlenecks: First, the imbalance between energy supply and demand: although the power consumption of bolt monitoring nodes is low (about 10 μW), the output power of existing micro acquisition devices is insufficient and difficult to match under low vibration conditions; Second, poor structural adaptability: traditional acquisition devices are mostly planar structures and cannot fit the curved surface of bolts; Third, insufficient environmental adaptability: the high humidity and strong vibration environment of the tower are likely to cause device failure, and the weather resistance needs to be improved.

C. RESEARCH CONTENT AND METHODS

1) Main Research Content

Analysis of wind turbine tower bolt failure mechanism and self-powering technology adaptability, clarifying monitoring parameters and power supply requirements; Innovative design of piezoelectric-electromagnetic composite self-powering device adapted to bolt scenarios, including structural optimization and development of energy management module; Construction and experimental verification of self-powered bolt health monitoring system, testing energy output characteristics and monitoring accuracy; Engineering application and economic evaluation of wind farms to verify the practicality and cost advantages of the technology.

2) Research Methods

Theoretical analysis: Using multi-physical field coupling theory to establish a piezoelectric-electromagnetic composite energy conversion model and analyze the correlation mechanism between bolt pre-tightening force and sensor signals; Simulation design: Conducting energy conversion efficiency simulation based on ANSYS, and structural strength and weather resistance simulation with COMSOL; Experimental verification: Building a simulated tower vibration/temperature difference platform to test the energy output, endurance capacity and monitoring accuracy of the device; Engineering application: Deploying 100 sets of systems in a northern wind farm and carrying out 6-month on-site operation tests.

II. BASIC THEORIES OF WIND TURBINE TOWER BOLT MONITORING AND SELF-POWERING TECHNOLOGY

A. FAILURE MECHANISM AND MONITORING REQUIREMENTS OF WIND TURBINE TOWER BOLTS

1) Bolt Failure Forms

Tower bolts mainly have three types of failure forms [5]: Fatigue fracture: alternating load leads to fatigue cracks at the root of bolts, accounting for 65% of total failures. Fracture analysis of a batch of bolts shows that the crack source is located on the outer surface of the root, and although the tensile strength reaches 1136-1220 MPa (meeting the standard), continuous stress cycles still cause fracture; Loosening failure: occurs when the pre-tightening force loss exceeds 20%, and the impact load during impeller start/stop is the main inducement, accounting for 25% of total failures; Corrosion failure: high humidity environment causes rust on the bolt surface, affecting the transmission of pre-tightening force, and such failures account for 15% in coastal wind farms.

2) Core Parameters of Bolt Health Monitoring

Combined with the failure mechanism, the core monitoring parameters include: Pre-tightening force: characterizes the bolt fastening state, with a critical threshold of 80% of the design value and a required accuracy of $\pm 5\%$; Strain: reflects the stress state of bolts, and the strain mutation amplitude before fatigue fracture is >150 $\mu\epsilon$; Vibration frequency: this parameter refers to the local vibration response of the bolt rather than the natural frequency of the overall structure. When the bolt loosens by 10%, the loss of pre-tightening force reduces the frictional damping between the bolt and the flange contact surface, decreasing local vibration energy dissipation; Temperature: the temperature increases by 3-5°C when the bolt is loosened due to increased friction, which can be used as an auxiliary judgment index.

3) Constraints of Tower Service Environment on Monitoring and Power Supply

The tower service environment forms multiple constraints: Vibration characteristics: the vibration frequency is 0.1-5 Hz under normal operation, the amplitude is 0.1-2 mm, and up to 10 Hz under extreme working conditions; Temperature difference range: the temperature difference of onshore wind power is -30°C$\sim$60°C, that of offshore wind power is -20°C$\sim$50°C, and the diurnal temperature difference can reach 20°C; Space limitation: the bolt spacing at the flange is usually only 50-80 mm (installation space <100 cm3); Environmental erosion: air flow containing salt and dust is likely to cause equipment corrosion, requiring a protection level of IP67.

B. CORE PRINCIPLES OF ENERGY SELF-POWERING TECHNOLOGY

1) Principle and Characteristics of Piezoelectric Energy Harvesting

The piezoelectric effect is a phenomenon in which piezoelectric materials generate electric charges under mechanical force, and its output charge density formula is:

$$Q = d_{33}F \tag{1}$$

where d_{33} is the piezoelectric constant (PC/N), and F is the external force (N). The d_{33} value of lead zirconate titanate (PZT) ceramics reaches 300-500 PC/N, which is suitable for vibration energy collection. The advantages of piezoelectric technology are fast response speed (<1 ms) and small volume, but the output is alternating current, which needs to be converted by a rectifier circuit, and the energy density is low (usually <10 μW/mm^3).

2) Principle and Characteristics of Electromagnetic Induction Energy Harvesting

Based on Faraday's law of electromagnetic induction, the coil cutting magnetic field lines generates induced electromotive force:

$$E = NBLv \tag{2}$$

where N is the number of coil turns, B is the magnetic induction intensity (T), L is the coil length (m), and v is the relative movement speed (m/s). Electromagnetic technology has stable output power and better performance than piezoelectric technology under low-frequency vibration, but it has a large volume, and the number of coil turns is limited after miniaturization (usually <1000 turns).

3) Principle and Characteristics of Thermoelectric Energy Harvesting

Based on the Seebeck effect, a loop composed of two different conductors generates thermoelectric potential under temperature difference:

$$V = \alpha \Delta T \tag{3}$$

where α is the Seebeck coefficient (μV/K), and ΔT is the temperature difference (K). The α value of bismuth telluride alloy reaches 200 μV/K, and the output voltage is about 4 mV when the tower temperature difference is 20°C, but the power density is extremely low (<1 nW/mm^3), which can only be used as an auxiliary power supply method.

C. COUPLING PRINCIPLE OF MULTI-ENERGY COMPLEMENTATION SELF-POWERING TECHNOLOGY

Multi-energy complementation technology realizes efficient utilization of different energy sources through the coordinated work of energy distributor, rectifier and energy storage unit: when the vibration is strong, the piezoelectric unit and electromagnetic unit dominate power supply, the output power is preferentially supplied to the monitoring node, and the surplus energy is stored in the supercapacitor; when the vibration is weak but the temperature difference is large, the thermoelectric unit is activated for auxiliary power supply, and the output voltage is adjusted to 3.3 V standard value through a DC-DC converter. The core of the coupling system is the energy switching strategy, which real-time monitors the output of each unit through a voltage sensor, and automatically switches to the main power supply mode when the power of a unit >50 μW. Micro vibration mode is defined as the working condition where the vibration frequency <0.5 Hz and the amplitude <0.2 mm.

D. ADAPTABILITY ANALYSIS OF SELF-POWERING TECHNOLOGY IN TOWER BOLT SCENARIOS

1) Energy Output and Environmental Matching Degree of Different Self-Powering Methods

It can be seen from the Table 1 that composite power supply has the highest matching degree in the bolt scenario and can cover the energy demand under different wind conditions.

TABLE 1. Energy Output and Environmental Matching Degree of Different Self-Powering Methods

Power supply method	Adapted environment	Output power (typical value)	Volume requirement	Weather resistance	Matching degree score
Piezoelectric	Medium and high frequency vibration	10–100 μW	Small	Excellent	8/10
Electromagnetic	Low frequency and large amplitude vibration	50–500 μW	Medium	Excellent	7/10
Thermoelectric	Large temperature difference environment	1–10 μW	Small	Good	5/10
Composite	Complex multi-working conditions	100–600 μW	Medium	Excellent	9/10

2) Analysis of Bolt Monitoring Power Consumption and Self-Powering Energy Supply-Demand Balance

The power consumption composition of a typical bolt monitoring node: strain sensing module (0.5 μW), data processing module (2 μW), wireless transmission module (48 μW, intermittent work). The system adopts low-power sensors and optimization strategies: the strain gauge uses the ultra-low power version of BF120-3AA, the vibration sensor is replaced with SCA100T-LP (intermittent working power consumption 1 μW), the temperature sensor DS18B20 (power consumption 0.3 μW), and the data transmission module uses the NB-IoT low-power module BC95-B5. Through optimizing the sampling interval (5 min/time) and data compression algorithm, the average power consumption is controlled at 50 μW. The output power of the composite self-powering device reaches 50 μW under the condition of 0.5 Hz vibration + 10°C temperature difference, and the surplus energy can be stored through the supercapacitor. A supply-demand balance model is established:

$$E_{store} = \int (P_{in} - P_{out})dt \tag{4}$$

where E_{store} is the stored energy, P_{in} is the power supply power, and P_{out} is the monitoring power consumption. Simulation shows that under the continuous windless condition (only temperature difference power supply), the energy storage unit can support the monitoring node to work continuously for 15 days, meeting the wind power operation and maintenance requirements.

III. INNOVATIVE DESIGN OF SELF-POWERING ENERGY HARVESTING DEVICE ADAPTED TO TOWER BOLTS

A. DESIGN OBJECTIVES AND CONSTRAINTS OF THE DEVICE

1) Design Objectives

Miniaturization: volume ≤35 mm×25 mm×8 mm, adapted to M30-M64 bolt installation; High efficiency: energy conversion efficiency ≥25% at vibration frequency of 0.1-5 Hz; Long service life: weather resistance up to IP67, working life ≥10 years; Low power consumption: the power consumption of the energy management module itself ≤1 μW.

2) Constraints

Installation space: the gap between the bolt head and the flange is usually <10 mm, and the device thickness must be ≤8 mm; Mechanical environment: resistant to vibration acceleration of 10 g and impact load of 50 g; Climatic environment: working temperature -30°C∼60°C, relative humidity 0-100%; Electrical compatibility: output voltage stable at 3.3 V±0.1 V, anti-electromagnetic interference.

B. INNOVATIVE DESIGN OF SINGLE-SOURCE SELF-POWERING ACQUISITION UNIT

1) Structural Optimization of Bolt-Integrated Piezoelectric Acquisition Unit

An arc-shaped piezoelectric ceramic design is adopted to fit the curved surface of the bolt head (the curvature radius is adapted to M30-M64 bolts), and the structure includes three layers: the outer layer is a 304 stainless steel protective shell, the middle layer is PZT-5H piezoelectric ceramic (diameter 20 mm, thickness 0.5 mm), and the inner layer is an epoxy resin buffer layer. The curvature of the ceramic is optimized through finite element simulation, and when the curvature radius matches the bolt, the energy conversion efficiency is increased by 42% compared with the planar structure. The peak-to-peak output voltage of the acquisition unit reaches 12 V, which can directly drive low-power sensors.

2) Miniaturization Design of Electromagnetic Acquisition Unit Based on Tower Vibration

An integrated "permanent magnet-coil" structure is adopted: a cylindrical neodymium iron boron permanent magnet (diameter 5 mm, length 8 mm) is fixed on the bolt head, and an enameled wire coil (wire diameter 0.05 mm, 800 turns) is encapsulated in the device shell. Power generation is realized by the relative movement between the permanent magnet and the coil generated by tower vibration, and the output power reaches 80 μW under the condition of 2 Hz vibration and 1 mm amplitude. The coil adopts vacuum potting technology to improve vibration resistance and weather resistance.

C. INNOVATIVE DESIGN OF MULTI-ENERGY COMPLEMENTATION SELF-POWERING MODULE

1) Design of Piezoelectric-Electromagnetic Composite Acquisition Structure

A coaxial integrated layout is adopted: the piezoelectric unit surrounds the bolt head, the electromagnetic unit is located at the center, and the thermoelectric unit (bismuth telluride alloy sheet, area 10 mm×10 mm) is attached to the outer wall of the device. The three are encapsulated into one body through epoxy resin, with an overall volume of 32 mm×18 mm×7 mm and a weight of only 15 g. The composite structure not only utilizes the bolt vibration energy but also captures the temperature difference energy between the device and the environment, realizing a power supply mode of "vibration-based, temperature difference-assisted".

2) Energy Coupling and Cooperative Output Control Strategy

An intelligent energy distributor is designed, which realizes three working modes based on STM32L051 low-power single-chip microcomputer: Strong vibration mode (vibration frequency >2 Hz): piezoelectric + electromagnetic units supply power in parallel, and the output power is preferentially supplied to the monitoring node; Weak vibration mode (0.5-2 Hz): piezoelectric unit is the main power supply, electromagnetic unit is auxiliary, and surplus energy is stored; Micro vibration mode (<0.5 Hz): activate the thermoelectric unit to supply power cooperatively with energy storage. The response time of the control strategy is <100 ms to ensure stable energy output under different working conditions.

D. DESIGN OF ENERGY MANAGEMENT AND ENERGY STORAGE MODULE

1) Design of Low-Power Energy Rectifier and Voltage Regulator Circuit

A full-bridge rectifier circuit is adopted to convert the alternating current of the piezoelectric/electromagnetic unit, with a rectification efficiency of 92%; the voltage is stabilized to 3.3 V through an LDO regulator (TC1185-3.3 V), which has a quiescent current of only 0.5 μA, saving 80% energy compared with traditional regulators. An overvoltage protection circuit is designed to automatically cut off the power supply when the input voltage >5 V to avoid damaging the monitoring module.

2) Selection and Matching of Micro Energy Storage Unit

A hybrid supercapacitor (capacity 1 F, withstand voltage 5.5 V) is selected as the main energy storage component, supplemented by a micro lithium battery (capacity 10 mAh). The supercapacitor is responsible for short-cycle energy buffering, and the lithium battery copes with extreme working conditions without energy input. The coordinated work of the capacitor and the battery is realized through a charge-discharge management circuit: when the capacitor voltage >3.3 V, power is supplied preferentially; when <2.5 V, the battery discharge is activated, and the charge-discharge cycle life is >100,000 times.

E. SIMULATION ANALYSIS AND OPTIMIZATION OF THE DEVICE

1) Finite Element-Based Simulation of Energy Conversion Efficiency

A composite device simulation model is established using ANSYS Mechanical, with vibration load (0.1-5 Hz, 0.1-2 mm amplitude) and temperature difference load (10-20°C) set. Simulation results show that under the condition of 2 Hz vibration + 15°C temperature difference, the total output power of the device reaches 120 μW, and the energy conversion efficiency is 28.7%; when the number of coil turns is optimized to 800, the efficiency of the electromagnetic unit is increased to 22%, which is the optimal parameter.

2) Simulation Verification of Structural Strength and Weather Resistance

Structural strength analysis is carried out through COMSOL Multiphysics: under the vibration acceleration of 10 g, the maximum stress of the device is 35 MPa, far lower than the yield strength of 304 stainless steel (205 MPa), and the structural safety factor reaches 5.8. Weather resistance simulation shows that the IP67 protection design can effectively block salt spray and dust, and the device material deformation is <0.01 mm within the temperature range of -30°C∼60°C, meeting the requirements of long-term service.

IV. CONSTRUCTION AND EXPERIMENTAL VERIFICATION OF SELF-POWERED BOLT HEALTH MONITORING SYSTEM

A. OVERALL ARCHITECTURE OF SELF-POWERED MONITORING SYSTEM

1) Integrated Design of Self-Powering Module, Monitoring Sensor Module and Data Transmission Module

The system adopts a hierarchical architecture with four layers: perception layer, power supply layer, transmission layer and application layer. The core components and functions of each layer are as follows: Perception layer: integrates strain gauge (BF120-3AA, sensitivity 2.0 mV/V) to measure pre-tightening force, vibration sensor (SCA100T, range ±2 g) to measure vibration frequency, and temperature sensor (DS18B20, accuracy ±0.5°C) to measure temperature; Power supply layer: the piezoelectric-electromagnetic-thermoelectric composite self-powering device designed in this paper provides continuous power for the perception layer; Transmission layer: adopts BLE 5.0 low-power Bluetooth module (CC2541, transmit power 0 dBm), and the data transmission interval is configurable (1-10 min); Application layer: the edge computing node processes the original data and uploads it to the cloud platform through the 4G module. Each module is integrated through a PCB board, with an overall size of 35 mm×25 mm×8 mm and a weight of 25 g.

2) Low-Power Control Strategy of the System

An "intermittent work-sleep wake-up" mode is adopted: the sensor module collects data once every 1 min (collection time 0.1 s), the transmission module sends data once every

5 min (sending time 0.5 s), and enters the sleep state for the rest of the time. The system power consumption in sleep mode is only 0.8 μW, saving 98% energy compared with the continuous working mode. Wake-up control is realized through voltage monitoring of the self-powering device: normal work when the energy storage voltage >3 V, and extend the sleep interval to 10 min when <2.5 V.

B. CONSTRUCTION OF EXPERIMENTAL PLATFORM

1) Laboratory Simulated Tower Vibration/Temperature Difference Environment Platform

Vibration simulation: an electromagnetic vibration table (JZK-10, frequency 0.1-50 Hz, amplitude 0-5 mm) is used to simulate the typical vibration of the tower at 0.1-5 Hz; Temperature difference simulation: a high and low temperature test chamber (GDJS-100, temperature range -40°C~80°C) is used to simulate diurnal and seasonal temperature differences; Monitoring equipment: a power analyzer (YOKOGAWA WT310, accuracy ±0.1%) is used to measure energy output, and an oscilloscope (Tektronix MSO24, bandwidth 70 MHz) is used to measure voltage signals.

2) Bolt Failure Simulation Test Bench

An M36 high-strength bolt flange connection test bench is built. The pre-tightening force (0-50 kN) is adjusted by a hydraulic wrench to simulate loosening failure; alternating load (10-40 kN) is applied by a fatigue testing machine (MTS 810, load range 0-100 kN) to simulate fatigue failure; a salt spray test chamber (YWX/Q-150, salt spray concentration 5%) is used to simulate corrosion failure. The test bench can real-time monitor bolt pre-tightening force, strain and other parameters, and compare with the data of the self-powered monitoring system.

3) Test Instruments and Data Acquisition System

Pre-tightening force calibration: torque wrench (CDI 2503MFRPH, accuracy ±3%); Strain calibration: static strain gauge (YE2538, accuracy ±0.1 $\mu\epsilon$); Data acquisition: NI cDAQ-9174 acquisition card, sampling frequency 100 Hz, synchronously recording data of the self-powered system and calibration equipment.

C. EXPERIMENTAL SCHEME DESIGN AND IMPLEMENTATION

1) Energy Output Characteristic Experiment of Self-Powering Device

Three groups of working conditions are set: Vibration frequency gradient experiment: fixed amplitude 1 mm, frequencies 0.5, 1, 2, 3, 5 Hz, measuring output power and conversion efficiency; Temperature difference gradient experiment: fixed vibration frequency 2 Hz, temperature differences 5, 10, 15, 20°C, measuring the output of the thermoelectric unit; Long-term stability experiment: simulating typical tower working conditions (2 Hz vibration + 15°C temperature difference), running continuously for 30 days, measuring the output voltage every day. Each group of experiments is repeated 3 times, and the average value is taken.

2) Endurance Capacity Experiment of Monitoring System

The endurance is tested under two extreme working conditions: High-energy condition: 5 Hz vibration + 20°C temperature difference, continuous operation, recording the change of energy storage voltage; Low-energy condition: 0.1 Hz vibration + 5°C temperature difference, simulating windless weather, recording the continuous working time of the system. External charging is turned off in the experiment, and only the self-powering device is used for power supply.

3) Bolt Health Parameter Monitoring Accuracy Verification Experiment

Three failure processes are simulated: Loosening process: the pre-tightening force is reduced from 50 kN to 30 kN (failure threshold), and data is recorded every 2 kN; Fatigue process: alternating load of 10-40 kN is applied for 1000 cycles, and strain is measured every 100 cycles; Corrosion process: placed in a salt spray test chamber for 7 days, measuring temperature and pre-tightening force every day. The measurement data of the self-powered system and the calibration equipment are compared to calculate the error.

D. EXPERIMENTAL RESULTS AND ANALYSIS

1) Analysis of Energy Output Stability and Efficiency of Self-Powering Device

The energy output characteristics of the self-powering device under different vibration frequencies (Table 2) show that when the frequency increases from 0.5 Hz to 2 Hz, the output power increases from 35 μW to 120 μW, and the efficiency increases from 18.2% to 28.7%; when the frequency >2 Hz, the efficiency growth slows down because the piezoelectric ceramic response enters the saturation zone. The temperature difference gradient experiment shows that the output power of the thermoelectric unit increases by about 2 μW for every 5°C increase in temperature difference, reaching 8 μW at 20°C temperature difference, which can be used as an effective supplementary energy source. In the long-term stability experiment, the output voltage fluctuation range of the device is 3.2-3.4 V, with a maximum deviation of ±2.9% and no obvious attenuation, proving that the energy output is stable and reliable.

TABLE 2. Energy Output Characteristics of Self-Powering Device under Different Vibration Frequencies

Vibration frequency (Hz)	Amplitude (mm)	Output power (μW)	Energy conversion efficiency (%)	Supplementary power of thermoelectric unit (μW, 15°C temperature difference)	Total output power (μW)
0.5	1	35	18.2	5	40
1	1	68	22.5	5	73
2	1	120	28.7	5	125
3	1	145	29.1	5	150
5	1	152	29.3	5	157

2) Comparison of Monitoring Data Accuracy

During the loosening process, the pre-tightening force measurement error of the self-powered system is <3% (Table 3), lower than the 5% error of the traditional wireless monitoring system; the strain measurement error during the fatigue process is <2 $\mu\epsilon$, consistent with the static strain gauge; the temperature measurement error during the corrosion process is ±0.3°C, meeting the monitoring requirements. The data transmission delay is <200 ms, equivalent to the digital twin system level.

TABLE 3. Comparison of Pre-Tightening Force Measurement Accuracy

Actual pre-tightening force (kN)	Measured value of self-powered system (kN)	Measured value of traditional wireless system (kN)	Error of self-powered system (%)
50	48.8	47.5	2.4
45	43.9	42.3	2.4
40	39.0	37.6	2.5
35	34.0	32.5	2.9
30	29.2	27.8	2.7

3) Evaluation of System Reliability and Environmental Adaptability

Under high-energy conditions, the system runs continuously for 30 days, and the energy storage voltage is stable at about 3.3 V without power failure; under low-energy conditions, the energy storage unit supports the system to work continuously for 32 days, meeting the extreme environment requirements. In the high and low temperature test, the system power consumption increases to 1.2 μW at -30°C, but it can still work normally; the output efficiency drops to 25.3% at 60°C, which is an acceptable range. The vibration impact test shows that the system works normally under 10 g acceleration without structural damage.

V. ENGINEERING APPLICATION CASE AND TECHNICAL AND ECONOMIC ANALYSIS

A. SELECTION AND IMPLEMENTATION OF ENGINEERING APPLICATION SCENARIOS

1) Basic Situation of Tower Bolts in Target Wind Farm

A northern wind farm (20 1.5 MW wind turbines, put into operation in 2018) is selected as the pilot. Due to the wind turbine position turbulence, the tower flange bolts of this wind farm have experienced 3 loosening failures. The target bolts are M36 high-strength bolts (grade 8.8), 108 bolts per unit, distributed on 3 flange surfaces of the tower (heights 20 m, 40 m, 60 m). The service environment: annual average temperature -5°C∼25°C, vibration frequency 0.5-3 Hz, maximum temperature difference 25°C.

2) On-Site Installation and Commissioning of Self-Powered Monitoring System

A "gasket-type embedded" installation method is adopted: the device thickness is strictly controlled at 8 mm, and the bolt head and flange gap reserves 2 mm buffer space to avoid mechanical extrusion during flange movement; the device edge adopts rounded transition design to reduce stress concentration risk. after removing the bolt, the self-powered monitoring device is attached to the bolt head and fixed with a matching nut, with an installation time of <5 min per bolt. A total of 100 sets of systems are deployed (5 key bolts per wind turbine), and the commissioning content includes: Bluetooth pairing: ensuring the transmission distance >10 m (covering the tower radius); Parameter calibration: calibrating the pre-tightening force sensor based on the measured value of the torque wrench; Energy test: recording the 24-hour energy output after installation to ensure >10 μW. The installation process does not require shutdown and has good adaptability.

B. APPLICATION EFFECT EVALUATION

1) Long-Term Operation Energy Supply Stability

The operation data from January to June 2024 shows that the average daily energy output of the system is 45 μW, and the energy storage voltage is maintained at 3.2-3.4 V. Only in February under extreme low temperature (-28°C), the voltage of 3 sets of systems temporarily drops to 3.0 V, but the monitoring is not interrupted. The energy supply stability reaches 99.2%, meeting the long-term operation requirements of wind power.

2) Bolt Health Status Monitoring and Fault Early Warning Effect

During operation, the system successfully warned of 2 bolt loosening incidents: On March 15th, the pre-tightening force of the 40 m flange bolt of Unit 3 decreased from 50 kN to 38 kN, and the vibration frequency rose to 45 Hz. The system triggered an early warning 72 hours in advance, and the operation and maintenance personnel tightened it when the wind speed was low to avoid fault expansion; On May 20th, the strain of the 20 m flange bolt of Unit 17 mutated, and the system generated a maintenance plan within 10 minutes, marking the bolt position and the required torque (error <5%). The early warning confidence is defined as the ratio of true positive early warning times to total early warning times in experiments and engineering applications. Based on the 6-month operation data of 100 sets of systems (23 effective early warning events in total, 22 of which are real faults), the early warning confidence is calculated to be 95.7%. The bolt failure frequency of the pilot unit decreased from 1.2 times per year to 0.

3) Performance Comparison with Traditional Power Supply Monitoring Systems

Compared with a wired monitoring system (Table 4), the self-powered system has significant advantages in deployment cost, operation and maintenance difficulty and service life, and the monitoring accuracy and response speed are equivalent.

TABLE 4. Performance Comparison of Different Monitoring Systems

Index	Self-powered system in this paper	Traditional wired monitoring system	Traditional battery wireless system
Deployment cost (Yuan/set)	2800	4500	2200
Installation time (min/set)	5	30	8
Operation and maintenance cycle (years)	10	2	1
Pre-tightening force measurement error (%)	< 3	< 2	< 5
Early warning response time (ms)	180	150	250
Environmental adaptability	IP67, -30°C∼60°C	IP65, -20°C∼50°C	IP66, -25°C∼55°C

C. TECHNICAL AND ECONOMIC ANALYSIS

1) Life Cycle Cost (LCC) of the System

Calculating the life cycle (10 years) cost with 100 sets of systems (20 wind turbines): Initial cost: hardware procurement 280,000 yuan (2800 yuan/set) + installation and commissioning 50,000 yuan = 330,000 yuan; Operation and maintenance cost: 5,000 yuan per year (only calibration, no battery replacement/wiring maintenance), totaling 50,000 yuan in 10 years; Total LCC: 380, 000 yuan, unit cost 3800 yuan/set·10 years.

2) Cost Comparison with Traditional Monitoring Methods

The 10-year LCC of the traditional battery wireless system: initial cost 220,000 yuan + operation and maintenance cost 400,000 yuan (battery replacement once a year, 400 yuan/set·time) = 620,000 yuan, 63.2% higher than the self-powered system; the 10-year LCC of the traditional wired system: initial cost 450,000 yuan + operation and maintenance cost 200,000 yuan = 650,000 yuan, 71.1% higher. In terms of economic benefits, the pilot wind farm reduced the loss of power outage due to faults by 18 million kWh (calculated at 0.3 yuan/kWh, worth 5.4 million yuan), and the annual operation and maintenance cost of a single unit was reduced by 32,000 yuan, with an investment payback period of about 8 months.

3) Economic Optimization Directions

Large-scale production: when the output reaches more than 1000 sets, the hardware cost can be reduced to 2000 yuan/set, and the LCC is reduced by 28.6%; Material substitution: using ceramic matrix composites instead of stainless steel shells reduces weight by 30% and transportation and installation costs by 15%; Service mode: adopting a "hardware + data service" subscription system, with a basic version of 800 yuan/unit per month, forming continuous revenue.

D. EXISTING PROBLEMS AND IMPROVEMENT SUGGESTIONS IN APPLICATION

1) Existing Problems

Under extreme low vibration conditions (<0.1 Hz), the energy output is insufficient and needs to rely on energy storage, resulting in limited endurance capacity; In the high salt spray environment of offshore wind farms, the corrosion rate of the device shell is accelerated, and the protection performance decreases slightly after 6 months; The Bluetooth transmission distance is limited (<15 m), and relay nodes need to be added when the tower diameter is large.

2) Improvement Suggestions

Adding a micro wind energy acquisition unit (based on triboelectric nanogenerator principle) to improve power supply under low vibration conditions; Treating the shell with fluorocarbon coating to extend the salt spray test life from 6 months to 2 years; Upgrading to BLE 5.2 protocol to increase the transmission distance to 50 m and reduce the demand for relay nodes.

VI. RESEARCH CONCLUSIONS

It is clarified that the failure of wind turbine tower bolts is mainly fatigue fracture (65%) and loosening (25%). The core monitoring parameters are pre-tightening force (accuracy ±5%), vibration frequency (0.1-50 Hz) and temperature (±1°C). Tower vibration (0.1-5 Hz) and temperature difference (10-25°C) can be used as energy sources for self-powering. An innovative piezoelectric-electromagnetic-thermoelectric multi-energy complementation self-powering device is designed: the arc-shaped piezoelectric unit is adapted to the bolt curved surface, and the energy conversion efficiency is increased by 42% compared with the planar structure; the micro electromagnetic unit has an output power of 80 μW under 2 Hz vibration; the total conversion efficiency of the composite device reaches 28.7%, with a volume of 32 mm×18 mm×7 mm, meeting the installation requirements of the bolt scenario. The built self-powered monitoring system realizes the integration of "acquisition-energy storage-monitoring-transmission", with an average power consumption of 8 μW and an endurance of 32 days under low-energy conditions; experimental verification shows that the pre-tightening force measurement error is <3%, the early warning response time is <200 ms, and it works stably in the environment of -30°C∼60°C. In the pilot wind farm application, the system achieved a 95% early warning accuracy, reduced the annual operation and maintenance cost of a single unit by 32,000 yuan, and demonstrated a life cycle cost over 63% lower than traditional systems, verifying the engineering practicality and economy of a technology highly relevant for high-reliability manufacturing.

AUTHOR CONTRIBUTIONS

Conceptualization –Wuwen Gao, Cheng Chen, Zhi Duan, Zhishe Chu, Manhong Jin and Panpan Wang; methodology – Wuwen Gao, Zhi Duan, Zhishe Chu, Manhong Jin and Panpan Wang; investigation – Wuwen Gao, Cheng Chen, Zhi Duan, Zhishe Chu, Manhong Jin and Panpan Wang; writing-original draft preparation – Wuwen Gao, Cheng Chen, Zhi Duan, Zhishe Chu, Manhong Jin and Panpan Wang. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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