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Mingyang HUANG

huang@ustb.edu.cn

University of Science and Technology Beijing

Research Article

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Posted Date: October 28th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10918505/v1>

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Additional Declarations: No competing interests reported.

Analysis of Wind Energy Management System Based on Controllable Wind Turbine Arrays and Wireless Control

Authors: Mingyang HUANG ^{a, b, c *}

^{*}Corresponding author (Mingyang HUANG, Email: huang@ustb.edu.cn)

Affiliations: ^a Key Laboratory of Intelligent Bionic Unmanned Systems, Ministry of Education, University of Science and Technology Beijing, Beijing 100083, P. R. China;

^b School of Artificial Intelligence, University of Science and Technology Beijing, Beijing 100083, P. R. China;

^c Institute of Artificial Intelligence, University of Science and Technology Beijing, Beijing 100083, P. R. China

[†]These authors contributed equally to this work

ABSTRACT

Wind power generation technology has been widely adopted, and improving wind energy utilization efficiency holds significant social and economic importance. To optimize the use of wind energy resources and reduce energy losses caused by the wake effect of wind turbines, this paper develops a wind energy measurement and control system that combines Zigbee communication technology with ultrasonic measurement technology.

In terms of the theoretical framework, customized wind turbine array configuration schemes are proposed for hilly areas and offshore environments respectively, and a physical demonstration model is used to illustrate the working principle of the system. In the theoretical analysis, combining actuator disk theory with conventional Computational Fluid Dynamics (CFD) methods, and using the NH1500 wind turbine as the baseline model, the dynamic impact of the upstream turbine's wake on the downstream turbine in a tandem configuration under different spacing conditions is investigated. Regarding wind turbine array design, two innovative arrays are proposed based on the model analysis results: an automatically adjustable-spacing array for offshore deployment, and a high-density array with large elevation differences for hilly terrains. These configurations can dynamically adjust the spatial layout of the wind turbine array according to real-time wind field conditions, thereby reducing wind energy loss.

In the aspect of the measurement and control subsystem, the "Intelligent Wind Energy Management

System Based on Ultrasonic Measurement" utilizes ultrasonic sensors to collect wind speed vector information in real time. This data is transmitted via a Zigbee network to achieve automatic yaw control of the turbines, while simultaneously sending wind condition data to the terminal control center. The control terminal processes the data, simulates the operating conditions of the turbines, calculates the wind energy utilization efficiency, and adjusts the wind turbine array to its optimal operating state through a wireless control system. This integrated approach realizes the intelligent management of wind energy resources, ensuring efficient and sustainable power generation.

Keywords: Wind Energy Management System; Wind Turbine Arrays; Wake Effect

1. Introduction

China currently possesses the world's largest cumulative installed capacity of wind power, marking significant progress in its renewable energy development ^[1]. However, when evaluating the maturity of China's wind power industry against global standards, distinct gaps remain. An analysis of per capita installed wind power capacity places China 34th globally, with 46W per person. In contrast, leading nations that also excel in total installed capacity—such as the United States, Germany, and Spain—have per capita values as high as 149.8W, 356.9W, and 356.9W, respectively ^[2]. Furthermore, regarding installed capacity per unit of land area, China ranks 25th globally at 6.5 kW/km², which is far below Germany's 81.4 kW/km² and Spain's 42.9 kW/km² ^[2]. These disparities indicate that China needs to further optimize its wind power development strategy, focusing on improving the efficiency and spatial distribution of wind energy infrastructure ^[3].

In current wind farm operations, economic losses primarily stem from the reduction in power output of downstream turbines due to interference from the wakes of upstream turbines ^[4, 5]. The ratio of power generation between a downstream turbine (P2) and an upstream turbine (P1) varies with the spacing distance (D) between them. Specifically, at a spacing of 4D, the downstream turbine generates only 54.5% of the upstream turbine's power; at 6D, it is 62.8%; and at 8D, it reaches 68.2% ^[6]. This phenomenon highlights the importance of avoiding the serial alignment of multiple turbines along the prevailing wind direction during wind farm layout planning ^[7].

A review of China's wind energy resource distribution map reveals that wind-rich areas are

mainly concentrated in the Inner Mongolia Plateau, the Qinghai-Tibet Plateau basin, and coastal regions ^[8]. Additionally, the hilly areas in the eastern and southwestern regions possess moderate wind resources but cover vast land areas and are located within economically active zones. Fully utilizing the wind resources in these coastal and hilly areas can effectively alleviate power shortages in the eastern regions and reduce the infrastructure investment and resource waste associated with long-distance power transmission ^[9].

To improve wind energy utilization efficiency and reduce energy losses caused by the wake effect, this paper proposes a wind energy management system based on controllable wind turbine arrays and a wireless control mechanism. Through theoretical modeling, customized configuration schemes for wind turbine arrays in hilly and offshore areas are proposed. Unlike traditional wind turbine arrays with fixed spacing and independent single-turbine yaw control ^[10], this system dynamically adjusts turbine spacing based on real-time data such as wind direction, wind speed, and angle of attack, thereby minimizing energy losses caused by wake vortices. Simultaneously, wireless control is utilized to finely adjust the yaw and pitch angles of the turbines via dedicated software based on the overall efficiency of the unit group. In hilly areas with slopes exceeding 20° , even if the same array spacing as in plains is used on the X-axis, the longitudinal (prevailing wind direction) spacing can be compressed to $2D - 5D$. Since most current wind farms maintain a $7D$ spacing, this approach effectively doubles the turbine density ^[11]. For deep-sea areas, a model is proposed wherein the turbine spacing can be autonomously adjusted according to wind field conditions. Implementing these control strategies can reduce the average wind energy loss in the power generation efficiency of turbine groups by 13% ^[12]. To the best of our knowledge, such a comprehensive description has not yet been found in existing literature.

The development and utilization of wind energy offer significant environmental benefits, including environmental protection, reduction of greenhouse gas emissions, augmentation of China's energy supply, optimization of the energy structure, and enhancement of energy security, making it a crucial measure for building a harmonious society ^[13]. At the same time, it greatly promotes the construction of a resource-saving and environment-friendly society in China and fosters sustainable economic and social development. Implementing this control method in hilly regions or offshore wind farms is expected to yield substantial economic and social benefits.

1.1 Research Background

Wind energy is one of the most commercially promising and dynamic renewable energy sources ^[1]. Wind power generation offers advantages such as significant potential for capacity growth, rapidly declining costs, safety, and an inexhaustible energy source. While providing a stable electricity supply for economic growth, wind power can effectively mitigate issues related to air pollution, water pollution, and global warming ^[13]. Among various new energy developments, wind power technology is relatively mature and possesses the conditions for large-scale commercial exploitation ^[3]. Against the backdrop of an increasingly severe global energy and environmental crisis, wind energy resources have begun to receive widespread attention.

From an international perspective, global cumulative installed wind power capacity has seen substantial growth in recent years. According to statistics from the Global Wind Energy Council, global newly installed wind power capacity reached a record high of 38 GW in 2009, with China accounting for one-third of this total. Between 2004 and 2009, the compound annual growth rate (CAGR) of global cumulative installed wind capacity was 27.09%, while the CAGR for newly installed capacity was 35.48% ^[14].

From a domestic perspective, China's wind power development in recent years has far outpaced other major wind power countries. China's wind power sector has maintained a strong momentum of development, doubling in size for four consecutive years. Furthermore, the technological level of wind power has improved significantly, and the industrial service system has been continuously perfected. Wind power is now basically equipped with the industrial conditions for large-scale development. By the end of 2009, China's total installed wind power capacity was 25.1 million kilowatts, accounting for 15.9% of the global total. The newly installed wind power capacity in 2009 was 13 million kilowatts, equivalent to 70% of the installed capacity of the Three Gorges Hydropower Station, making China the world's largest market for newly installed wind power capacity ^[14].

1.1.1 Existing Technology

AC doubly-fed variable-speed constant-frequency wind power generation systems have garnered increasing attention due to their small-capacity power electronic converters, superior input-output characteristics, and simple control systems ^[15]. Wind in nature follows its own nonlinear laws, resulting in considerable instability in wind measurement. In existing similar wind

power management systems, most instruments merely transmit signals by simply modulating analog signals into digital ones, necessitating the exploration of better data processing methods ^[16].

This paper innovatively adopts ultrasonic measurement technology, encompassing signal amplification, analog-to-digital conversion, data processing, and data encoding. Three-dimensional ultrasonic wind speed measurement can accurately acquire wind speed vector information ^[17]. This information is then transmitted in real-time using Zigbee to control the automatic directional adjustment (yaw) of the wind turbines, while simultaneously feeding back wind condition information to the terminal control center ^[18]. The control terminal can utilize the returned data to simulate motor operating conditions and calculate wind energy utilization efficiency, achieving intelligent wind energy management.

The turbine orientation is automatically adjusted through Zigbee transmission and automated processing, enabling real-time monitoring and management via the terminal. The experimental instrumentation features advanced, complete, and highly integrated testing functions. It employs high-precision probes and heating equipment, among others. The terminal control equipment adopts a centralized mode for batch input/output of data and enables remote control.

1.1.2 Technical Features

Ultrasonic wireless transmission avoids mechanical wear, reduces costs, and improves the information reception rate ^[17].

The use of Zigbee wireless control technology to drive automatic motor adjustment offers advantages such as low power consumption, low cost, low complexity, speed, reliability, security, support for a large number of network nodes, and support for various network topologies ^[18].

Turbine orientation is automatically adjusted via Zigbee transmission and automated processing, allowing for real-time monitoring and management through the terminal.

All received signals can be converted into digital signals and fed back to the terminal for software processing, realizing intelligent management.

Solar-assisted power supply is adopted, with battery power used to reduce the frequency of replacements ^[19].

Unified data encoding facilitates further data processing or secondary transmission.

1.2 Research status at home and abroad

Optical fiber is a type of waveguide that guides light waves, serving as a novel transmission medium. Optical fiber communication is a method of communication that uses light waves as the carrier and optical fibers as the transmission medium. The research into using optical fibers as an optical transmission medium has undergone an arduous journey. It was not until 1966 that Dr. Charles K. Kao published a seminal paper theoretically elucidating the possibility of achieving low-loss information transmission through optical fibers, after which the development of optical fiber technology began to accelerate at an extraordinary pace ^[20]. Following 1970, which is hailed as the inaugural year of optical fiber communication, advancements in the technology propelled fiber optic systems into the practical application stage.

With the development of optical fiber communication and sensing technologies, the application of optical fibers has been expanded across numerous fields. Simultaneously, research into fiber optic technology itself has progressed rapidly. Optical fiber communication technology, which utilizes optical fibers as the information transmission medium, stands as a significant hallmark of the new technological revolution and serves as the primary transmission tool for various information networks in the future information society.

In 2008, Shanghai Fudan Tianxin Scientific & Educational Instrument Co., Ltd. developed the FD-OFT-A Audio Signal Optical Fiber Transmission Experimental Apparatus ^[21]. This instrument enables the optical fiber transmission of audio signals, allowing students to understand the working principles of optical modulation, transmission, and demodulation, thereby gaining a preliminary insight into optical fiber communication. Similarly, Minks Instruments (USA) introduced the YJ-GY-II Audio Signal Optical Fiber Transmission Technology Experimental Apparatus, which features functions and parameters essentially identical to those of the instrument from Shanghai Tianxin ^[21].

2. Design scheme

2.1 Theoretical part

2.1.1 Boundary model

The design scheme introduces the most widely used wake model in current engineering applications - the Park model. This model is based on the assumption^[22,23]:

(1) The initial diameter of the wake area is the diameter of the wind turbine. (2) The growth rate of the wake area shows a linear relationship.

Its boundary model can be expressed by the following formula:

Among them, y_{park} is the wake boundary position of the Park model; D is the diameter of the wind turbine; x represents the downstream position of the wind turbine; The wake diffusion coefficient k is closely related to topographic factors and can be expressed as:

$$k = \frac{0.5}{\ln(\frac{h}{z_0})} \quad (2)$$

Among them, h and z_0 are respectively the center height of the hub and the artificial surface roughness. In the fan model we selected, these two values are 100mm and 100mm respectively^[24].

From this, we calculated the wake field (Figure 1)

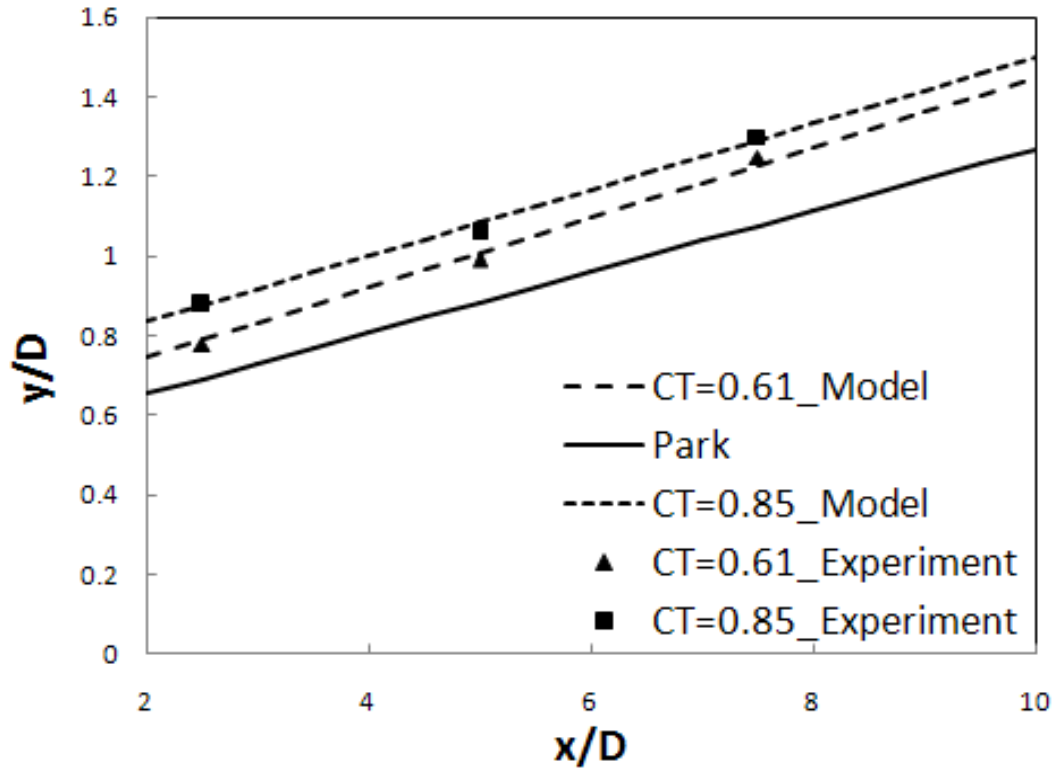


Figure 1 shows the comparison of the established wake boundary model, the wake boundary model of the Park model and the experimental data

Obtain the calculation formula of the wake boundary:

$$y_{park} = D/2 + 0.153791967x \quad (3)$$

2.1.2 The selection of the optimal fan distance based on the influence of wake

Given that the typical spacing between upstream and downstream turbines in wind farms is approximately 7D, this study focuses on the wake field positions at 4D, 5D, 6D, 7D, and 8D downstream of the rotor plane. The axial velocity distributions at these five positions, obtained using the generalized actuator disk method, are shown in Figure 2 ^[25]. In the figure, the horizontal axis represents the ratio of the radial position (r) to the rotor diameter (D), while the vertical axis represents the ratio of the axial velocity (V_x) to the initial free-stream velocity (V_0). The axial velocity across each cross-section follows a normal distribution along the turbine's central axis. As the airflow velocity recovers within the wake field, the centerline velocity shows a continuous upward trend, increasing from 68% of the free-stream velocity at 4D to 81% at 8D. However, the rate of airflow velocity recovery decreases as the distance from the turbine center increases. Furthermore, it is observed that the overall recovery speed of the airflow velocity within the wake field gradually slows down from 4D to 8D. This may be attributed to the more intense mechanical turbulence generated by the rotor in the wake field closer to the turbine. Higher turbulence intensity leads to more vigorous momentum exchange between fluid particles, thereby accelerating the airflow recovery speed. In summary, through the analysis of airflow velocity distribution at different downstream locations, it is evident that with greater spacing between tandem turbines, the downstream turbine is less affected by the upstream turbine's wake field. Through aerodynamic and power generation analyses, the relative power generation ratio of the downstream turbine to the upstream turbine is obtained, as shown in Figure 3 ^[6].

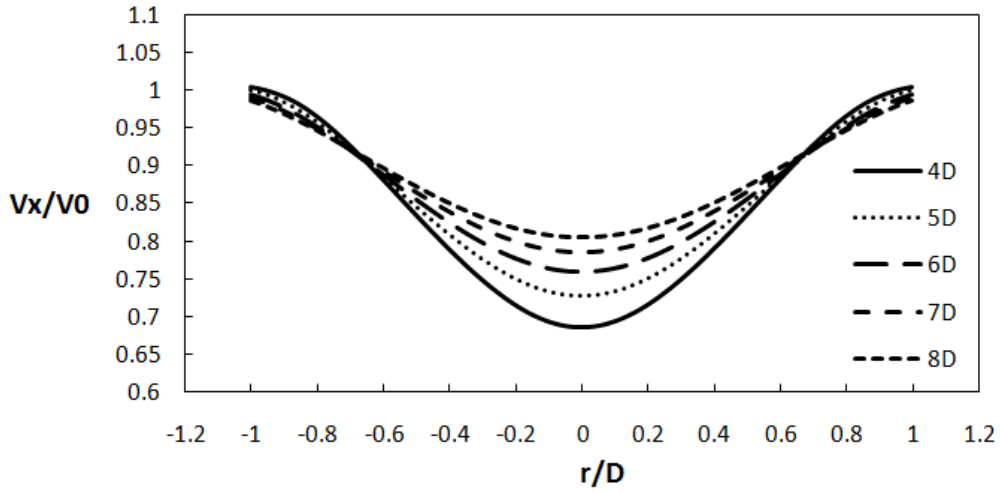


Figure 2 shows the axial velocity distribution at different positions downstream of the wind turbine.

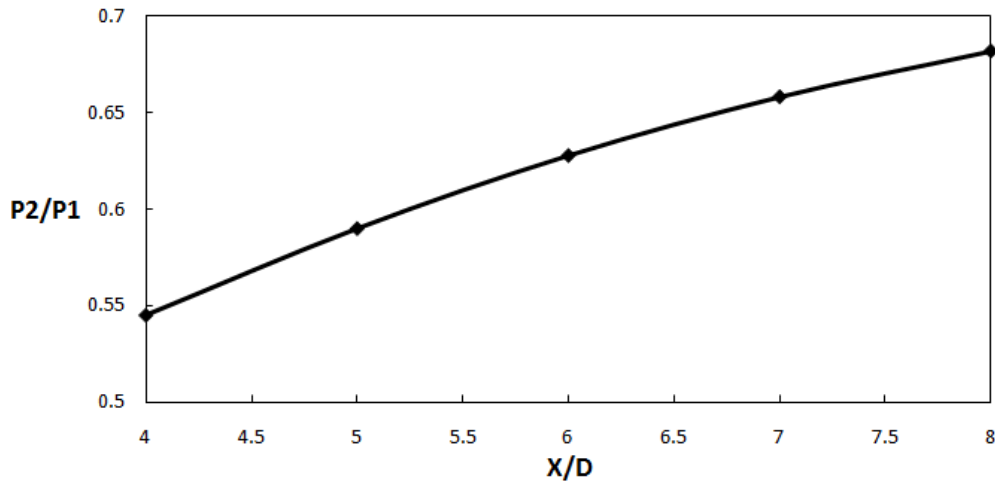


Figure 3 shows the ratio of the generating power of downstream wind turbines to that of upstream wind turbines.

Therefore, we come to the conclusion:

When facing the wind direction and the distance between two adjacent wind turbines is 8D, the influence of the wake is the least.

The wake interference can be reduced to within 5% only when the r/D value reaches 0.8.

3) The ratio of the power generation capacity (P_2) of the downstream wind turbine to that of the upstream wind turbine varies with the distance between the two wind turbines. The power generation capacity of the downstream wind turbine at position 4D is only 54.5% of that of the upstream wind turbine, 62.8% at position 6D, and 68.2% at position 8D^[6]. This indicates that even if the distance between two serial-arranged wind turbines reaches 8D, the power loss of the downstream wind turbines is still relatively large. Therefore, during the arrangement of wind

turbines in the wind farm, it is necessary to pay attention to avoiding the serial arrangement of multiple wind turbines in the main wind direction.

2.2 A simulation sand table of wind turbine arrays in hilly terrain

The ideal slope model is established as shown in the following figure:

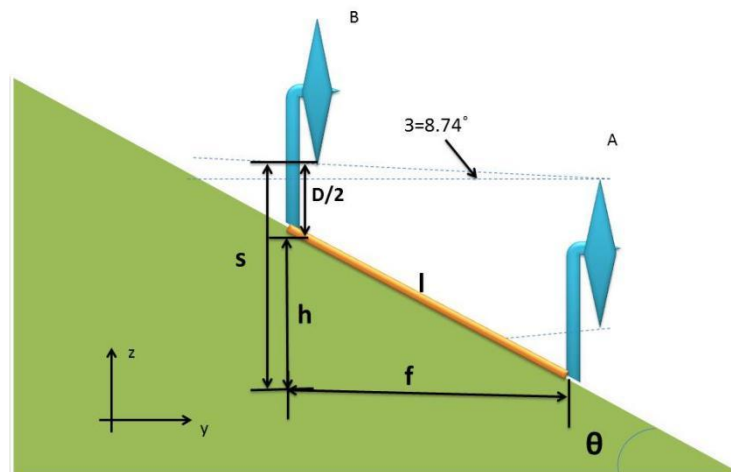


Figure 4 slope model

To simplify the complexity of the model, we only consider the component of wind speed parallel to the Y-axis direction, that is, ignore the kinetic energy loss caused by the elevation Angle and the viscosity of the near-ground surface. According to the Park model, we know that the Angle between the upper boundary of the tail flow of wind turbine A and the horizontal y direction is $\beta = 8.74^\circ$ ^[22]. At this point, the influence of the wake effect generated by fan A on B can be ignored.

The results show that in hilly areas with a slope greater than 20 degrees, even if the same array spacing as in plain areas is adopted in the X-axis direction, since the spacing in the longitudinal (main wind direction) direction can be compressed to between 2D and 5D, that is, the wind turbine density can be increased by about twice^[11]. Therefore, the laying density of wind turbines can be increased in hilly areas. Based on the conclusions in 2.1, we present the sand table model (physical object).



Figure 5 sand table model

It respectively shows the density at which the fans can be laid under different slope conditions. On a 30° slope, we also demonstrated an array of yaw functions based on wireless control using stepper motors.

2.3 Wireless control system

2.3.1 Zigbee wireless communication module

This system uses the Zigbee communication module of the CC2530 series developed by TI Company and adopts the IEEE 802.15.4 network communication standard, which is capable of realizing information transmission^[18]. In this system, three nodes are used to simulate the entire process of control. The first node serves as the node for collecting signals. That is, the speed and direction are measured by the ultrasonic speedometer and the data are transmitted to the node through asynchronous communication, and then to the second node. The second node acts as the node for collecting signals and sends the collected signals to the PC for processing and display by the PC. And the processed result is passed to the third node, thereby controlling the motor drive to make the fan rotate. The microcomputer principle of its communication will not be elaborated again.



Figure 6 Zigbee wireless communication module

2.3.2 Ultrasonic measurement module

In this system, this module was independently designed and produced by us. The working principle is that ultrasonic waves need to be propagated through an air medium. Therefore, the relative motion of the air medium will affect the propagation speed of ultrasonic waves. By using the time difference method to measure the relative velocity of the wind movement in the measurement area in three directions in the three-dimensional space respectively, information such as the direction and intensity of the wind can be fitted^[17]. The circular structure in the above picture is the measurement module.

2.3.3 Control terminal module

The monitoring software is developed by programming in C++. The difficulty lies in making the results have a good operation interface and analyzing and feeding back the working conditions of each fan.

2.3.4 Solar power supply module

Considering the need for energy conservation and environmental protection as well as the convenience of device replacement, for the measurement and zigbee transmission modules, we have adopted solar power supply circuits, enabling the measurement modules to work independently and facilitating installation and replacement^[19]. The main technical difficulty lies in the adoption of the charge and discharge control circuit and the automatic switching controller of the mains power.

2.4 Controllable array model of the wind turbine

In the far sea areas, the sea-land breeze is no longer the dominant wind direction. The sea wind direction is influenced by relatively stable factors such as long-term ocean currents and the Coriolis force on the surface. Compared with onshore areas, the intensity of wind turbulence on the sea surface is low, and there is no influence of complex terrain factors. Moreover, the power of wind turbines installed at sea is relatively large. Theoretically, a considerable distance should be maintained to make the most effective use of wind energy. However, considering the huge cost of laying submarine cables in deep-sea areas, with a service life of 20 years, the management cost will also be extremely high. At the same time, Offshore wind energy resources also have regional distribution characteristics, which all limit that offshore wind turbines should also be distributed in clusters^[9].

To this end, we have proposed a method of using variable spacing to avoid the energy loss caused by the tail flow effect of the wind turbine in a small area. The proposal of this model is based on the currently applied suspended horizontal-axis wind turbine and is realized by utilizing the instability of the parallelogram. When the wind direction changes, the spacing of the fans in the wind direction can be adjusted by regulating the Angle between the two sides of the fan array. At this point, if the relationship between the included Angle and the side length and the distance between the fans in the wind direction is given, the situation can be transformed into the conclusion of the fan array in the plain area. It has been verified that if the shape of the wind turbine is taken into account, when the connection distance of the wind turbine is $4D$, the variation range of the included Angle only needs to be about 30° to minimize the wind energy loss in the 120° direction^[12].

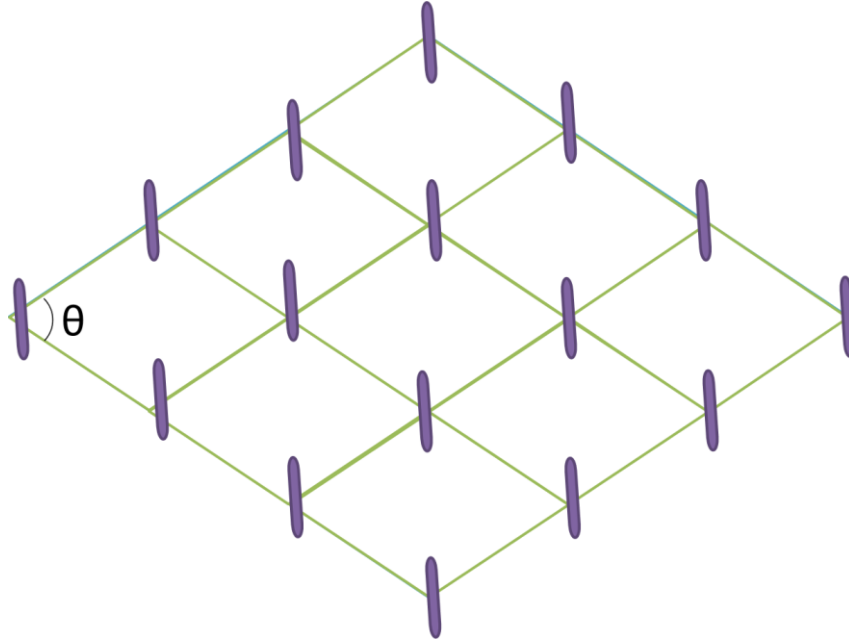


Figure 7 Schematic diagram of the adjustable wind turbine array model

Its transformation announcement is (a and b are respectively the horizontal and vertical spacings of the wind turbine array in the plain area) :

$$a = L \cos\left(\frac{\theta}{2}\right)$$

$$b = 2L \sin\left(\frac{\theta}{2}\right) \quad (4)$$

The system needs to convert the vector information of the wind and other environmental information into digital signals and feed them back to the control terminal and the drive section:

① Signal acquisition, signal amplification, analog-to-digital conversion, data processing and data encoding are carried out at the ultrasonic measurement end, and then real-time transmission is conducted using zigbee^[17,18].

② At the drive end, tasks such as signal conversion, data decoding, data processing, digital-to-analog conversion, power amplification, and drive operation are completed;

③ At the control terminal, the received signals are decoded and analyzed through software to obtain relevant parameters and data, and the wind energy situation is intelligently processed internally to achieve intelligent management.

Its features are as follows: Real-time information of the working window environment of the fan is obtained by ultrasonic measurement, and the orientation of the motor is automatically

adjusted through zigbee transmission and automated processing. Real-time monitoring and management can also be achieved through the terminal.

2.5 Main components and working principle

According to the overview, the circuit features of the experimental instrument are composed of three modules: a receiving device that uses ultrasonic measurement to convert signals and restore digital optical signals to audio analog signals, and an optical fiber transmission cable connecting the transmitter and the receiver.

With FPGA as the core, the digital signals of the transmitting module and the receiving module are processed respectively. On the one hand, real-time signal transmission is achieved; on the other hand, real-time signal measurement is carried out. The optical fiber transmission channel for digital signals: It is composed of amplifiers and filters, analog-to-digital converters and digital-to-analog converters, serial transmitters and receivers, optical-to-electrical converters and electro-optical converters, read and write interfaces of programmable logic device FPGA chips, transmission optical cables, etc. The LCD screen needs to display the relevant results when sampling sinusoidal signals: ① Sampling points; ② Sampling time interval; ③ Sampled voltage analog value ④ Signal type. In addition, for each sampling point, the binary digital external oscilloscope outputs the timing waveform diagram to obtain the comparison relationship between the analog and digital values of the same signal.

To meet and adapt to the basic requirements of experimental teaching content, the instrument also has necessary auxiliary functions, such as sound playback, sound wave monitoring, high and low frequency discrimination, etc. It is equipped with functional basic unit modules such as function signal generators, audio signal power amplifiers, and music memory, to meet and improve the matching requirements for various experiments.

3. The hardware design of the instrument

3.1 The implementation schemes of each component hardware circuit

The implementation schemes adopted for each part of the circuit are shown in Table 1 as follows:

Table 1. Selection Scheme Table of Hardware Circuits for Each Part

Circuit Module	Technical Implementation
Power Circuit	Switching power supply provides 12V DC. Voltage regulator chips L7805, ASM117-3.3, and ASM-1.5 provide 5V, 3.3V, and 1.5V DC
FPGA Control Circuit	Altera Cyclone I EP1C3T100C8N with 18.432MHz crystal oscillator
Filtering	2nd-order anti-aliasing filter using LM324 quad op-amp
A/D Conversion	Cirrus Logic CS5342 (24-bit ADC) and CS4334 (DAC)
Data Conversion	SN65LV1023A (Serializer) and SN65LV1224A (Deserializer)
Optical Conversion	HNMS-XEMC41XSC20 transceiver (1310nm/1550nm)
Display	LCD12864 with blue background and white text
Signal Generator	ICL8038 precision wideband op-amp
Storage	ISD4000 E2PROM chip

3.2 The hardware structure of the system

The signal channel consists of two major parts: the optical receiver and the optical transmitter. The two are connected by optical fibers. The working principles of light emission and light receiver are interrelated; one is the reverse process of the other. The optical transmitter converts the electrical signal of audio into an optical signal, and the optical receiver converts the optical signal into the electrical signal of audio ^[21].

The optical transmitter is composed of the following circuit modules: filter amplification, A/D conversion, control section, parallel/series conversion, and electrical/optical module section.

3.3 System circuit design

3.3.1 Power supply

The entire circuit is powered only by a 12V DC power supply. The internal integrated circuits require power supplies of 5V, 1.5V and 3.3V. The 5V power supply is provided by the L7805 three-state regulated power supply, while the 3.3V and 1.5V are respectively provided by ASM117-3.3 and ASM117-1.5.

3.3.2 The data processing and real-time control part of FPGA

The circuit adopts the FPGA of model EP1C3T100C8 as the main control chip, and the working clock is directly provided by the crystal oscillator of 18.432MHz. The chip has two clock input terminals. Select one to input the crystal oscillator clock. Since all the modules of the FPGA are used, each module needs to be powered and grounded.

There is a phase-locked loop inside the FPGA, which can perform frequency division and frequency doubling to obtain different frequencies. The clocks of the analog-to-digital conversion chip and the parallel/series conversion chip in the transmitter are provided by the FPGA. Since the output is serial binary data after analog-to-digital conversion and the data input of the parallel/string converter is 10 bits, encoding is required in the FPGA. The encoding should avoid the consecutive appearance of multiple "0s" and "1s" as much as possible, and adopt the 8B-10B encoding method. Inside the FPGA, the serial binary data is first decomposed into 8-bit parallel data, and then output through 8B-10B encoding. The FPGA in the receiver provides the working clock of the digital-to-analog converter and the reference clock of the serial-to-parallel converter, and decodes the ten-bit data output by the serial-to-parallel converter and restores it to eight-bit data for transmission to the digital-to-analog converter. The functions of FPGA are implemented by Verilog programming, and the program is downloaded to FPGA using the AS (Active) configuration method.

3.3.3.1 Filtering and amplification part

When sampling audio signals, if the signal contains more than half of the sampling frequency and the sampling frequency is not high enough, aliasing signals will occur. Aliased signals cannot be removed by digital filtering methods; hardware filtering is required. The sampling frequency of A/D conversion needs to be 2 to 10 times higher than the highest frequency of the audio signal. According to the bandwidth of the required audio signal and the characteristics needed for

anti-aliasing filtering, a second-order low-pass active filter with a cut-off frequency greater than or equal to 20kHz is designed. The designed circuit is shown in Figure 8.

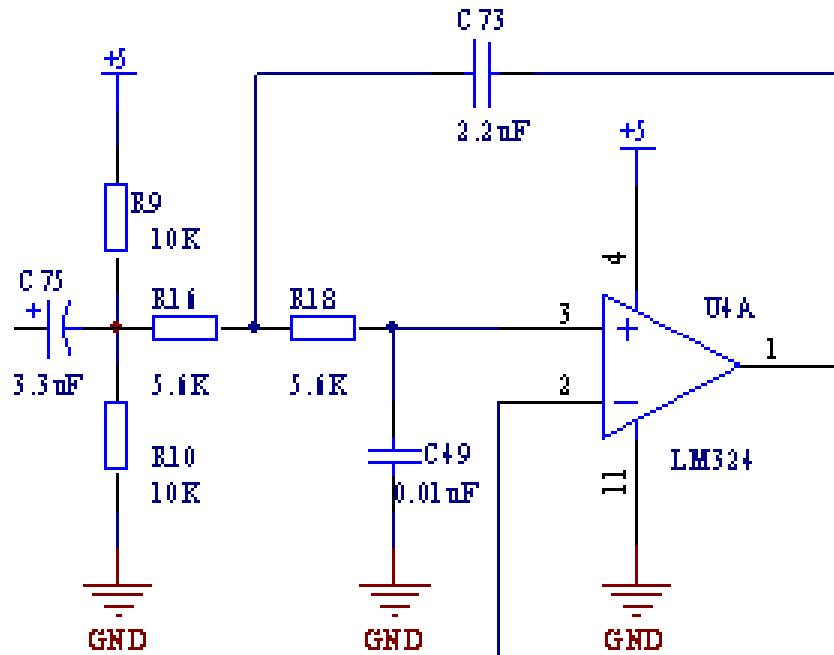


Figure 8 Audio filtering and amplification circuit diagram

Meanwhile, this circuit has the function of isolation amplification, and the integrated operational amplifier adopts the LM324 powered by a single power supply. This is an amplifier with integrated four operational amplifiers, low power consumption and a wide voltage operating range. It has the ability of internal compensation and a relatively low input bias current. It has a bandwidth of 1.2MHz when operating on a 5V power supply. Since the audio signal is input through two channels and the bandwidth of sound that the human ear can distinguish is 20Hz to 20kHz, the LM324 is sufficient to meet the requirements. This is a single-sided channel, and the other channel is the same as it.

The LM324 in the picture is powered by a 5V power supply and is amplified in one stage. A certain voltage bias should be added when the signal is input.

3.3.3.2 A/D Conversion Section

The analog-to-digital conversion circuit adopts the professional audio processing integrated chip CS5342 produced by Cirrus Logic. Its working clock frequency is set at 18.432MHz and is provided by FPGA. The signal is input through the AINL and AINR pins, SDOUT outputs the

converted serial binary data, and LRCK and SCLK output the sampling frequency. Pins M0 and M1 are respectively connected to the high and low levels to ensure that the chip operates in the double-speed active mode, generating a sampling frequency of 96MHz through frequency division. In addition, the RST pin is set to a high level, and appropriate filter capacitors are added to various reference voltage pins to ensure the chip operates stably and correctly. Its circuit is shown in Figure 9.

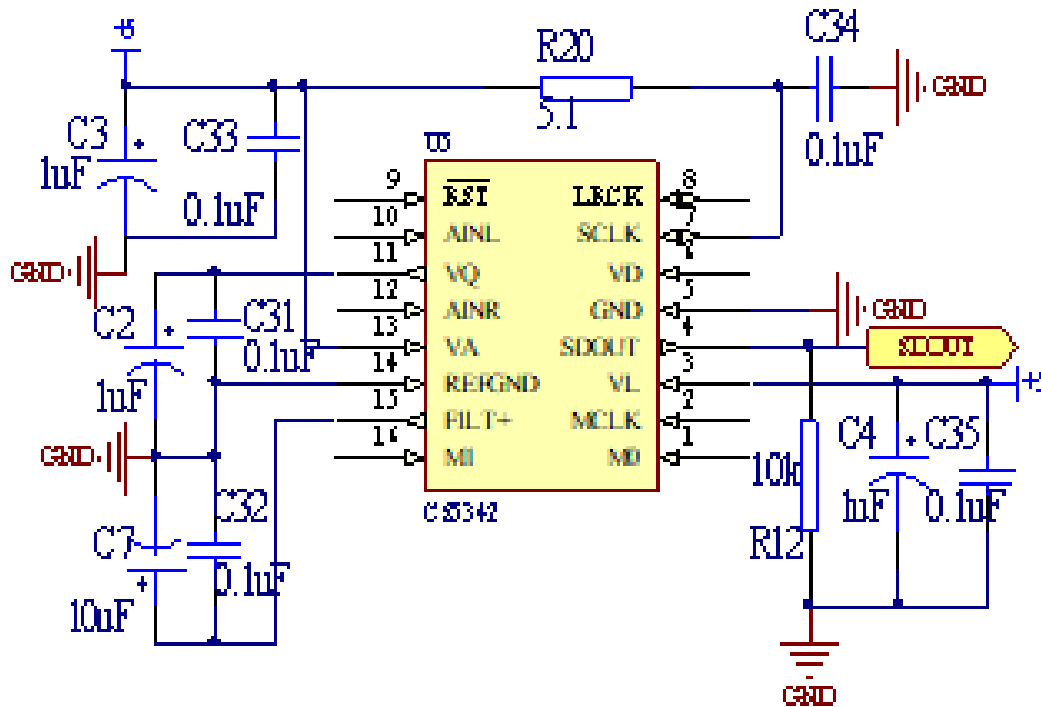


Figure 9 A/D conversion circuit diagram

3.3.4 Signal transmission part

The data processed by FPGA needs to be sent through optical fibers. First, the parallel data needs to be converted into serial data, and then the serial data needs to be converted into optical signals.

3.3.4.1 Parallel/series conversion

The circuit is implemented using the serializer SN65LV1023A integrated chip. The corresponding receiving end is accomplished by the deserializer SN65LV1224A integrated chip. The SN65LV1023A can convert 10-bit parallel data into a serial differential data stream, and this differential data stream can be restored to 10-bit parallel data by the SN65LV1224A. This group of

chips has a phase-locked loop inside and can match its own clock for data output. The reference clock of the serializer SN65LV1023A is set to 18.432MHz. Data is input at this clock frequency, and the internal matching of its chip generates a data output clock. Each 10-bit parallel data is converted into 12-bit serial data, with an additional start bit and a stop bit. Therefore, the effective frequency is 184.32MHz. The reference clock of the decoder is also set at 18.432MHz to meet the data transmission requirements.

Since the audio signal is real-time and continuous, the generated data stream proceeds continuously. Therefore, the circuit cannot be set to enter the high-impedance state or power-saving mode. As a result, both DEN and PWRDN of LV1023 are set to high potential.

The accurate transmission of serial data requires the synchronization of the serializer and the deserializer. This group of chips adopts a random synchronization method. The SYNC1 and SYNC2 of the serializer are left floating. The LOCK of the deserializer is input into the FPGA to implement control over data transmission.

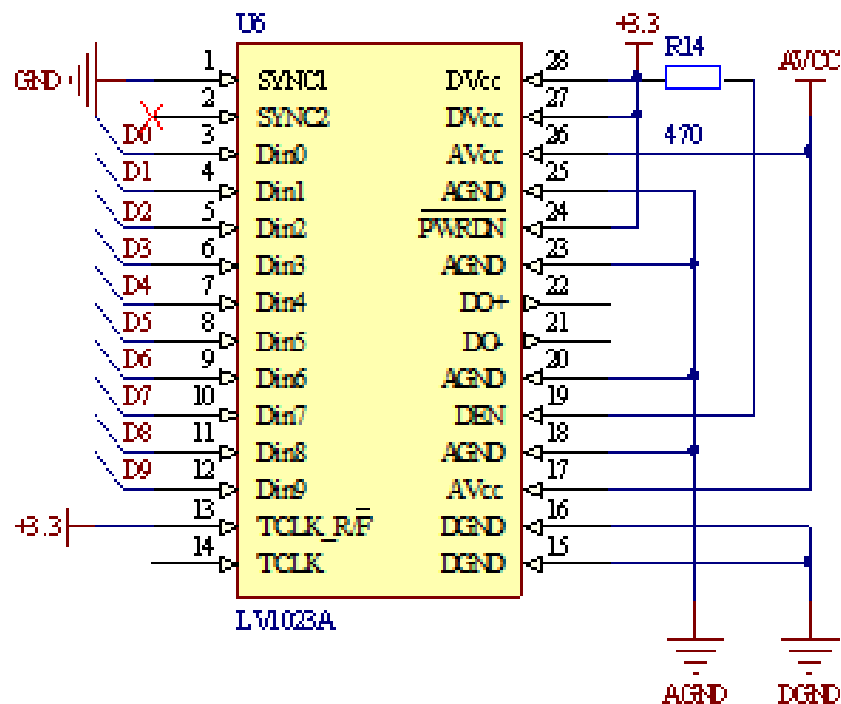


Figure 10 Parallel/Series conversion circuit diagram

3.3.4.2 Electrical/optical module

A single-fiber bidirectional integrated transceiver module of model HNMS-XEMC41XSC20

with a working wavelength of T1310nm/R1550nm is adopted to convert the differential data flow of electrical signals into optical data signal flows ^[21], and the circuit is shown in Figure 11.

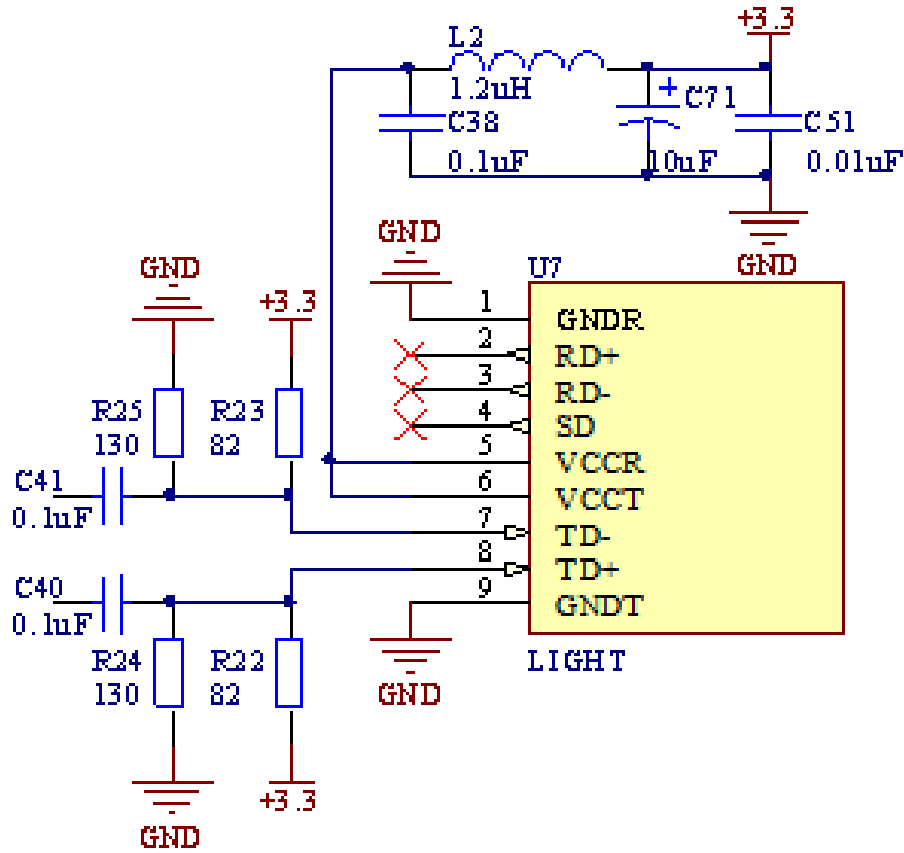


Figure 11 Circuit diagram of the optical emission module

3.4 Signal reception and processing

3.4.1 Optical/electrical conversion module

This experimental device transmits signals using a single fiber. After the optical signal is transmitted to the receiving device, it needs to be restored to an electrical signal, that is, the differential voltage data stream. A single-fiber bidirectional integrated transceiver module of model HNMS-XEMC41XSC20 with a working wavelength of T1310nm/R1550nm is adopted to convert optical signals into electrical signals ^[21]. The converted differential signal is output by RD+ and RD-. The circuit is shown in Figure 12.

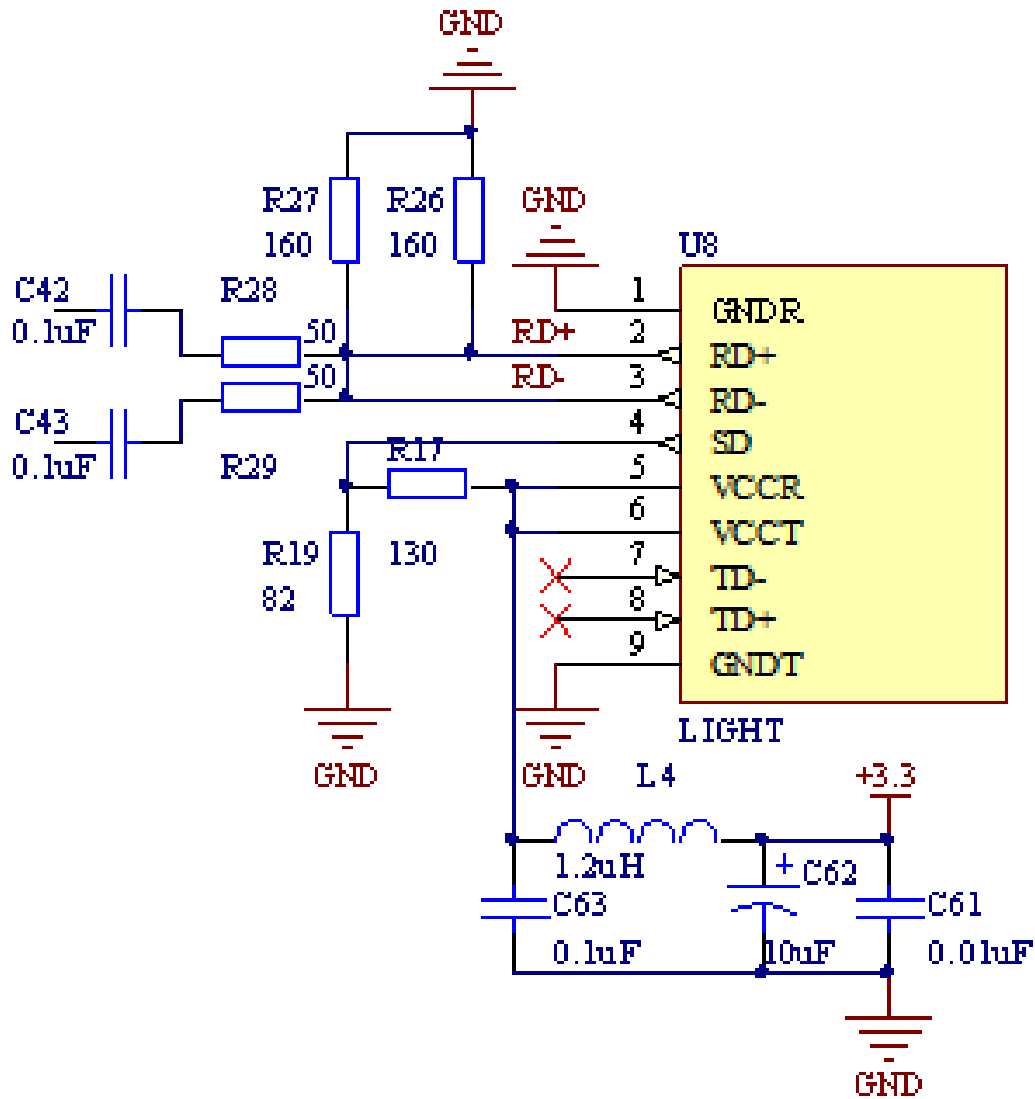


Figure 12 Photoelectric conversion circuit diagram

3.4.2 Serial-to-parallel conversion

The serial-to-parallel conversion device adopts the deserializer SN5LV1224A that matches the deserializer SN5LV1023A in the transmitter. The serializer in the transmitter converts 10-bit parallel data into a serial differential data stream. Therefore, a corresponding deserializer is needed in the receiver to restore the serial differential data stream to parallel data. The SN5LV1224A has a phase-locked loop inside. When receiving data streams, it can automatically match the receiving clock based on the frequency of the data. Externally, only a reference clock needs to be provided for it. The reference clock here is selected as 18.432MHz, which is provided by the FPGA control section. The chip also matches a clock that is synchronized with the data after decoding to facilitate the parallel data output after conversion. To ensure the continuity and real-time performance of the

audio signal, it is necessary to avoid the chip being in power-saving mode or high-impedance mode. Therefore, PWRDN and REN need to be connected to a high level. Connect RCLK-R/F to a high level, that is, select the rising edge of the clock to output data.

This group of chips has two synchronization methods: fast synchronization and random synchronization. Fast synchronization is achieved by a serializer sending a set of synchronization signals composed of six consecutive "1" and "0". After receiving the signals, the serializer locks the data clock. Before the locking is completed, LOCK remains at a high level. After the synchronization is completed, it jumps to a low level. The transmission of the synchronization signal is controlled by SYNC1 and SYNC2 of the serializer. As long as one of them is set to a high level for more than six clock cycles, the serializer begins to continuously send the synchronization signal. Fast synchronization has the advantages of being fast and accurate. However, in long-distance signal transmission, optical fibers only transmit data and cannot well transmit the SYNC and LOCK signals of the serializer and unserializer. Therefore, the random synchronization method is adopted. The random synchronization mode serializer does not need to send a synchronization signal. The deserializer directly locks the data stream to achieve synchronization. After the lock is lost, the deserializer will re-lock the clock. Connect LOCK to the FPGA for real-time control.

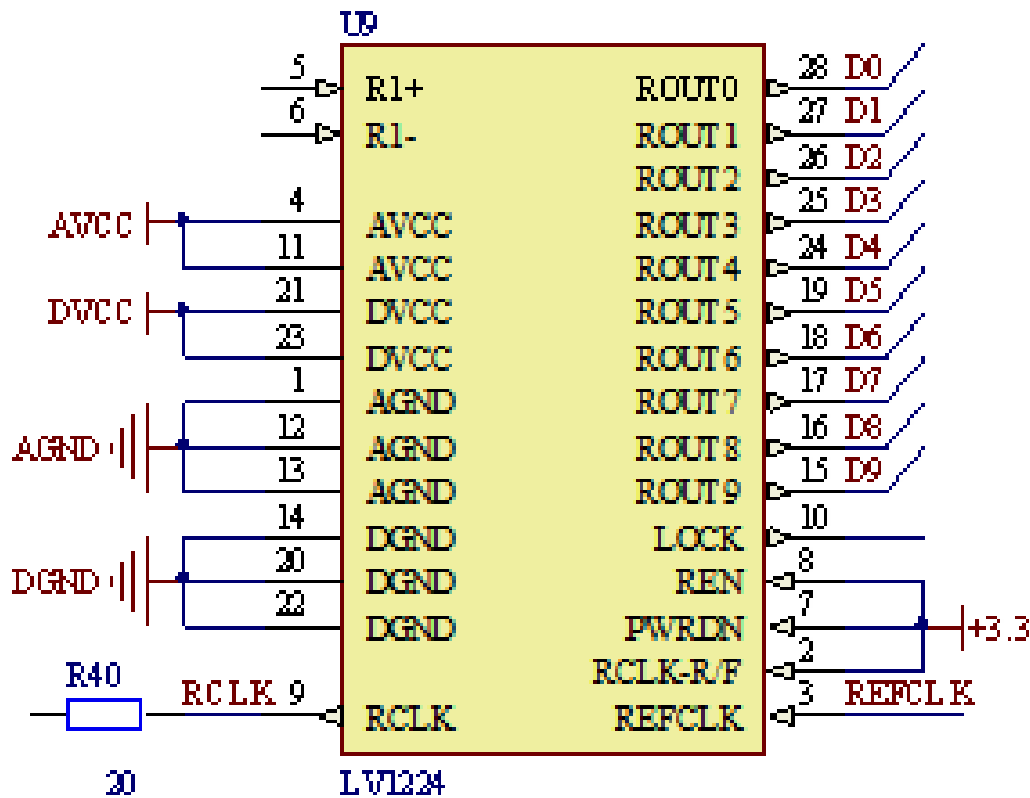


Figure 13 Series/Parallel conversion circuit

3.5 D/A conversion and video signal output

The D/A conversion part adopts the professional audio signal processing chip CS4334 produced by Cirrus Logic. This chip features a complete stereo DAC system with strong anti-interference ability, low distortion and noise, and adopts a single-voltage +5V power supply. The chip has two clock modes, namely the external serial clock mode and the internal serial clock mode. When the chip operates in the external serial clock mode, the de-emphasis filter cannot be accessed, and the external serial clock is prone to interference. Therefore, the internal serial clock mode was adopted in the design of this device. The serial clock SCLK is generated internally and synchronized with the master clock MCLK(18.432MHz) and the sampling clock RLCK(96KHz, generated by FPGA frequency division). After the signal is converted from digital to analog, the left and right channel analog signals are output by AOUTL and AOUTR respectively. After low-pass filtering, they are output. Since the maximum output of the signal can reach 3.5V at full scale and the device can amplify the audio signal through an external amplifier, the amplification processing of the audio signal is not carried out in this design.

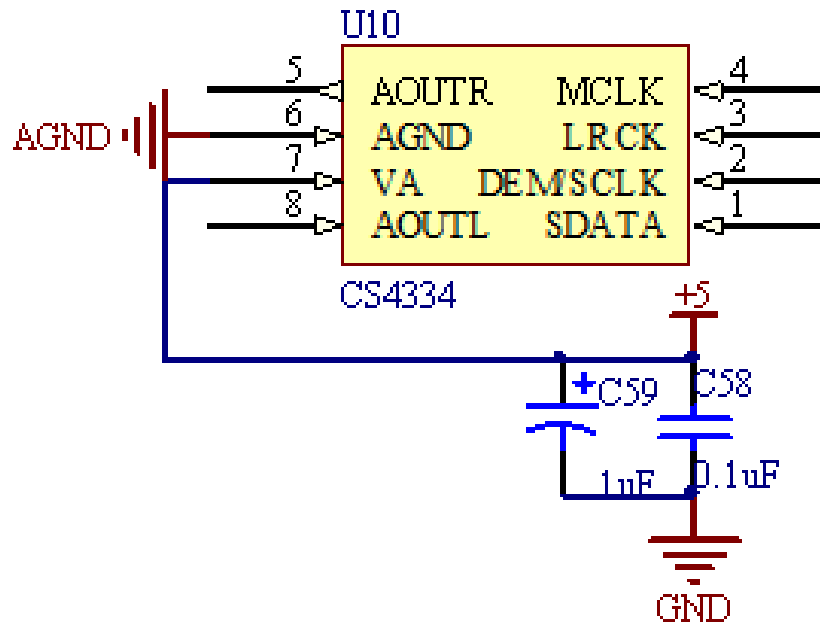


Figure 14 D/A conversion circuit diagram

4. Software design

The system is programmed using VerilogHDL language and edited and simulated in the Quartus II environment. The FPGA chip completes tasks such as AS encoding, decoding, LCD screen display control, and the identification and execution of various functions. The program is downloaded to the FPGA chip in the AS (Active) configuration mode.

8B-10B encoding is a commonly adopted encoding method in high-speed serial communication at present. It converts 8-bit data into 10-bit data, balancing the number of "0" and "1" in the converted data stream, ensuring that the DC component of the transmission is close to 0 and minimizing baseline drift. It not only avoids errors caused by excessive repetition of "0" or "1" during the transmission process, but also prevents data loss due to clock drift or synchronization loss at the receiving end. It has the DC compensation function, which can ensure that there is no DC offset in the link over time, improve the performance of line transmission, facilitate the receiver to capture the synchronous clock more accurately, and the use of specific code elements can enable the receiving end to align the code elements more accurately. The encoding process is shown in Figure 15. When programming, directly call the IP core of the codec and connect the corresponding pins.

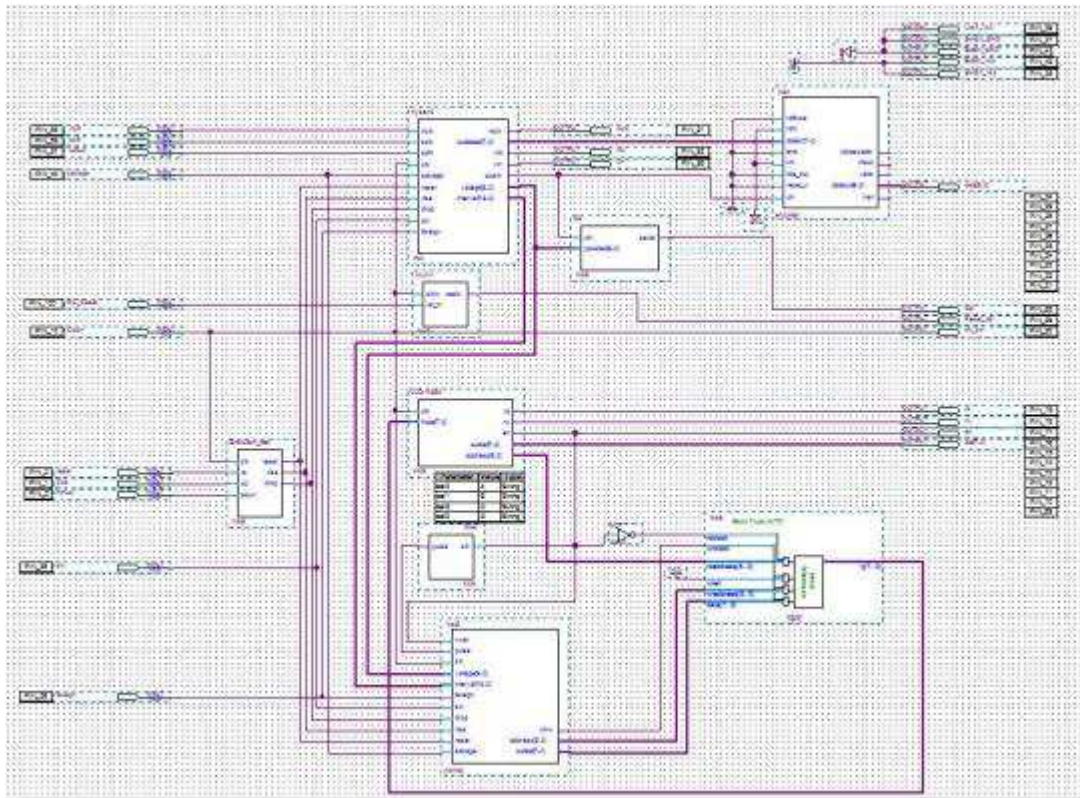


Figure 15 Software structure diagram of the sending end

This instrument boasts an invention patent, filling the gap in the field of basic experiments in universities. In terms of structural combination, it features a flexible design: the transmitting module and receiving module can be integrated into a single chassis, resulting in a compact, lightweight, and easily movable whole machine. Alternatively, they can be separated into two independent chassis—one dedicated to digital processing and signal transmission, and the other responsible for signal reception and restoration—with the two connected via optical fibers for seamless operation. Functionally, it excels in signal testing: it enables real-time signal acquisition and data processing, and the binary digital external oscilloscope at each sampling point outputs timing waveforms. This allows students to reproduce analog waveforms by tracing points during experiments, deepening their understanding of the forms and characteristics of digital signals. It also offers audio-visual experience capabilities: users can either store music or connect external music signals, and enjoy clear audio playback through the instrument's built-in speaker or connected headphones, achieving effects comparable to regular audio systems. By connecting an external oscilloscope for audio signal monitoring, users can observe and recognize signals intuitively. This combination not only helps in understanding the relationship between sound and electrical signals but also enhances the interest of the entire experimental process. Moreover, the

instrument adopts multiple encoding methods to represent digital quantities, which can be customized according to the teaching needs of different disciplines and levels. Its attractive appearance, reasonably designed control panel, and complete set of buttons and knobs further facilitate convenient human-machine interaction.

5. Working principle and performance analysis

Based on the aerodynamic theory and experimental data, the wake interference among multiple wind turbines was modeled, analyzed and simulated^[4,22]. Design the wind turbine array model and establish an information monitoring and automatic control network based on wireless communication technology to further optimize the management of important renewable resources that are currently popular in research.

After actual measurement, the wireless control system can achieve functions including: wind condition information collection, information transmission, terminal display and feedback regulation. Among them, the measurement module adopts the MSP430 microcontroller and an 8MHz crystal oscillator. The theoretical measurement accuracy can reach 0.02m/s, the measured error is (+-) 0.1m/s, and the working power is less than 1w. Theoretically, the wireless communication module can cover a working area of tens of square kilometers by adding routers^[18].

6. Innovation points and applications

Based on the new aerodynamic experimental and theoretical analysis data, wind turbine arrays suitable for hilly and far-sea areas were designed respectively^[11,12].

The Zig-bee communication technology, ultrasonic measurement technology and software technology are organically combined^[17,18]. Each module can work independently without the need for line connection. By using ultrasonic technology to measure wind speed, three-dimensional vector information of wind speed can be obtained. The collection module can be powered by solar energy, which is in line with the trend of low carbon and environmental protection^[19].

The potential of wind energy resources available for development in our country is extremely

huge. The total exploitable capacity of wind energy resources both offshore and onshore is approximately 1,000 to 1,500 GW. In 2011, the newly added installed capacity was 18GW. By then, China's total installed capacity had reached 62.4GW, exceeding a quarter of the global installed capacity^[14]. The new expectation is that by 2020, China's total installed capacity of wind power will reach 150 to 200GW^[1].

By analyzing the different influences of the wake generated by the upstream wind turbine on the downstream wind turbine when the spacing between two tandem wind turbines is different, we designed a high-density wind turbine array in hilly areas and a variable-pitch array in far-sea areas where the wind turbine spacing can be changed according to the wind field conditions^[11,12]. According to theoretical analysis, adopting this regulation method can reduce wind energy loss by more than 13% in the group power generation efficiency of wind turbines^[12]. Under the condition that the total power generation remains unchanged, it can save twice the area of the wind farm, thereby reducing the difficulty of cable laying and lowering maintenance costs, etc. Although this regulation method is currently rather difficult to implement in engineering, considering the improvement of wind turbine installation technology, the economic and social benefits that this paper may bring will still be very considerable.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Acknowledgments

This work was supported in part by no Fund.

human participants

NOT APPLICABLE

Funding Declaration

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Ethics statement

This study involved secondary analysis of de-identified data obtained from existing datasets. No new participants were recruited for the present study. Ethical approval and informed consent were obtained by the original investigators at the participating sites. The present study used only de-identified data released for research purposes under the corresponding data-use terms.

Code availability

The code used for model training, evaluation, explanation analysis, and visualization is available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT and Codex (OpenAI) to assist with language editing, manuscript organization, and formatting. After using these tools, the authors reviewed and edited the content as needed, verified the scientific content, numerical results, and references, and take full responsibility for the coclinical trial numbertent of the publication.

Clinical trial number

NCT followed by an 8-digit number (NCT00000419).

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