Design of deicing device for wind turbine blade based on microwave and ultrasonic wave

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Abstract: Nowadays, wind turbine deicing has become a hot research topic. The traditional deicing method of blade has many problems, such as high energy consumption, low efficiency and low effect. In order to solve the above problems, the project team designed a wind turbine blade deicing device based on microwave and ultrasonic wave. During the operation, two deicing methods, namely microwave thermal energy, ultrasonic cavitation effect and thermal effect, were used to deice in stages to achieve the purpose of high efficiency and energy saving. The whole device is composed of walking system, microwave system and ultrasonic system, and the operation of the device is realized by the electrical control part. Compared with the existing deicing methods, the device can achieve the purpose of low energy consumption and high efficiency deicing; in addition, the device has the advantages of flexible mechanism for control, less pressure on wind turbine blades, and low cost.

1. Introduction
At present, there are still many defects and deficiencies in the existing deicing methods of wind turbine blades at home and abroad. It is particularly important to explore a new effective deicing method. This device focuses on the clean and environmental protection utilization of wind energy, and designs a kind of blade deicing device using microwave heat energy and ultrasonic sound energy, which solves the problem that the existing deicing methods are not ideal. At the same time, the device avoids only using a single deicing method, which has better deicing effect and shorter time, and greatly improves the deicing efficiency. In addition, considering the economic cost, the device reduces the investment in the device cost and improves the economic value of wind energy utilization on the premise of ensuring the deicing effect of the device, which has a broad market prospect and promotion value.

2. Design scheme
The device consists of walking system, microwave system and ultrasonic system. Among them, the walking system uses 57 stepper motor to drive the device to run and ensure the safety of the device; the microwave system uses the microwave heating principle to melt the ice; the ultrasonic system uses the ultrasonic cavitation effect and thermal effect to shatter and melt the remaining ice. The overall schematic diagram of the device is shown in Figure 1.
The walking system consists of three parts, namely suction cup module, rolling brush module and moving module; the microwave system is composed of three parts, namely microwave antenna, magnetron device and cooling fan; the ultrasonic system is composed of three parts, namely stepping motor, nut lifting mechanism and transducer. As shown in Figure 2 is the technical roadmap of the device.

3. Mechanical structure

3.1 Walking system

3.1.1 Suction cup module
As the whole device is working at high altitude, it is faced with problems such as high wind speed, high wind speed and wet blade surface. In order to ensure the stability and safety of high-altitude operation of the device, the project team adopts the vacuum negative pressure adsorption method to realize the stability and safety of the device, and installs suction cup modules in four directions of the whole device. Figure 3 shows the structure diagram of the suction cup module. When the device is still, the vacuum generator only needs to draw air once to make the suction cup absorb negative pressure; when the device starts to move, the air inlet valve of the generator is opened to vent air, and the negative pressure in the suction cup is adjusted to ensure that the device can walk without friction and keep the suction cup in negative pressure adsorption state.

According to Newton’s second law when the device is subjected to sliding friction in the horizontal
direction, it can be estimated that:

\[ F_p - \mu (G + \frac{nS\Delta P}{\alpha}) = ma \]  

(1)

In the formula, FP is the wind force of force 12, which is 116.8n; \( \mu \) is friction coefficient, which is 0.25; G is gravity of the device, which is 450N; n is the number of suction cups, which is 4; P is the pressure difference (vacuum degree) between inside and outside the unit area, which is 0.918kg/cm²; s is the area of suction cup, which is 52.8cm²; \( \alpha \) - safety factor, is 3.

According to formula (1), the sliding friction force of the device can reach 128.657n, which is greater than the maximum wind force of 116.8n when the blade of 1.5MW wind turbine is working (see Annex 1 for the analysis and calculation process). Therefore, after installing the suction cup, the device can safely "walk" on the blade within the wind force range of normal operation of the wind turbine.

3.1.2 Rolling brush module
Due to the snow on the ice surface of the blade, if the snow on the ice surface cannot be removed, the subsequent deicing work will be difficult to carry out smoothly. Therefore, the project team designed a rolling brush module for removing snow on the surface of ice. Firstly, the shaft of the roller brush is fixed on the snowboard, and the shaft is driven to rotate by the DC motor, and the snow is swept out along the inner cavity of the snow shield.

3.1.3 Mobile module
The project team uses rubber track wheel system as transmission mechanism. The track wheel system is installed in the square groove at the rear end of the device, and the sprocket wheel is driven to rotate by installing a motor, and the drive wheel of the sprocket and chain makes the driving wheel rotate, and finally drives the track to roll stably. Figure 4 is the schematic diagram of electric track wheel.

3.2 Microwave system
The microwave system is the first deicing system of the device. The magnetron converts the electric energy into microwave energy and transmits the energy through the microwave antenna directionally to raise the ice surface temperature and achieve the purpose of deicing. In order to avoid the influence of temperature rise on magnetron, a cooling fan is equipped. The number 1 represents the microwave antenna, the number 2 represents the cooling fan, and the number 3 represents the magnetron.

Figure 4 Schematic diagram of electric track wheel

1-square groove, 2-track, 3-drive wheel, 4-shaft, 5-bearing seat
6-sprocket, 7-chain, 8-coupling, 9-motor, 10-supporting wheel

Figure 5 schematic diagram of microwave system structure
(1) Magnetron: it converts electric energy into microwave energy. In order to achieve the highest conversion efficiency, the project team selects the air-cooled magnetron with the frequency of 2.45GHz. The maximum output power can reach 1kW, and the conversion efficiency is more than 70%.

(2) Microwave antenna: transmitting microwave energy and orienting the generated microwave. The antenna radiates microwave energy on the wind blade substrate, and the substrate medium and microwave couple and generate heat, so as to realize the purpose of deicing.

After comparative study of various antennas, the project team determined that the horn antenna with large power capacity, easy to shape and simple structure is more suitable for microwave radiator of the system. The horn antenna consists of a uniform waveguide and a horn gradually opening from the waveguide mouth. By using CST software simulation, the horn antenna is modeled. By analyzing the half power angle frequency of antennas with different horn length and width, the half power angle line graphs of E-plane and H-plane under different conditions are obtained, as shown in Figure. 6. The smaller the half power angle of H plane and the higher the power concentration, the slower the microwave loss speed on the horizontal plane. Considering the chassis height of deicing device, the antenna material is determined to be PEC, the antenna length is 380mm, the width is 280mm, the height is 270mm, and the wall thickness is 2mm. At this time, the half power angle of E-plane is 22.9 ° and that of H-plane is 22.65 °. Figure 7 shows the structure of horn antenna.

In addition, the positive orientation unit in CST is called as the microwave source. The magnetron frequency is set at 24.5ghz and the output power is 1.25kw. The microwave inlet is the magnetron mounting port on the antenna for simulation. Fig. 8 shows the simulation diagram of microwave far-field direction. According to the polar diagram, after entering the antenna from the entrance, the distribution of microwave in the antenna is more uniform, and the residual amount is less, so the damage to the equipment is small, and the main radiation direction is directly below the antenna port, which meets the requirements of the project team for the antenna.

In order to verify the effect and feasibility of microwave heating, the project team established the model according to the basic parameters of general material FRP and FRP medium for wind turbine substrate, and completed the experiment with the help of computer system.
According to the temperature distribution diagram, the temperature of the area where the blade surface is facing the microwave antenna outlet is higher than that of other areas, which indicates that the antenna has a good effect on the microwave aggregation and the heating area is concentrated, which indicates that the scheme of microwave heating the wind blade substrate is feasible. In addition, it can be seen from the figure that the temperature decreases with the increase of depth, and the temperature difference between the front and back sides reaches 30 °C. In order to avoid damage to the blade caused by the temperature rise, it is necessary to control the microwave heating time, that is, stop heating when the surface temperature of the wind turbine substrate reaches 0 ~ 4 °C.

(3) Cooling fan: cooling effect.

### 3.3 Ultrasonic system

Ultrasonic system is the second deicing system of the device, which is mainly composed of stepping motor, nut spin lifting mechanism and transducer. Firstly, the screw nut is driven by stepper motor and synchronous belt to rotate in place, so as to drive the lifting table to move vertically. Finally, the transducer is used to separate the residual icing from the blade.

In addition, in order to select the appropriate frequency ultrasonic transducer, the project team used ANSYS software to calculate the coupling of piezoelectric structure without considering the microwave thermal effect. The stress distribution nephogram of icing surface calculated by ANSYS software is shown.

In the simulation, a certain volume of GFRP, ice coated body and transducer are selected. The piezoelectric ceramic of the transducer is disc-shaped, with a radius of 18mm and a thickness of 5mm. PZT-4 composite material is used. The voltage is applied on the upper and lower surfaces and fixed on the aluminum bell mouth. After the model is established, the model is meshed to generate a large number of nodes, and the loading frequency ranges from 20kHz to 60KHZ. After calculation, the stress amplitude frequency curves of several ice covered edge nodes and the corresponding stress values at the icing boundary are checked.

When the peak frequency is 41khz, the stress of several important nodes in XY and XZ directions is investigated. The results are shown in Table 1. Since the maximum adhesion stress of icing is 0.4MPa, according to the data in Table 1, the shear stress in XY and XZ directions can meet the deicing requirements when the frequency is 41khz. According to the actual processing conditions, the project team selects the transducer with frequency of 40KHz in the system.

| Node number | 1  | 2  | 3  | 4  | 5  |
|-------------|----|----|----|----|----|
| shear stress in XY plane | 0.8146 | 0.6814 | 0.4175 | 0.8697 | 0.5877 |
| shear stress in XZ plane | 1.0393 | 0.9986 | 0.4941 | 0.4272 | 0.2139 |

### 4. Electrical control part

Large capacity lithium battery is used for power supply and wind turbine is used for charging. The upper computer sends the execution command to each module of the lower computer through Bluetooth communication; the lower computer receives the command to operate the walking system, microwave system and ultrasonic system, and sends the relevant information back to the upper computer in real time.

#### 4.1 Suction cup control module

The specific process of vacuum generation and venting of suction cup is as follows: after 12V power supply is connected, the output current of single chip microcomputer is expanded through triode drive and connected to the port of solenoid valve; PWM signal is output to control on-off. If the solenoid valve receives the power on signal, the coil is energized, the vacuum generator suction valve is opened for a
period of time and then closed, and the suction cup is adsorbed; if the power-off signal is received, the coil is powered off, the vacuum generator inlet valve is opened, and the suction cup is released.

4.2 Mobile remote control module

This module is used to walk the remote control device and ensure its walking safety, which is divided into three parts. (1) PID algorithm is used to control gw600 worm gear motor to drive the crawler, and the speed difference between two groups of track motors is used to control the steering. (2) The us-015 ultrasonic sensor installed on the side of the device is used to measure the horizontal distance from the device to the blade edge, and then the ranging data is sent back to the upper computer. The upper computer processes the data to judge whether the device is at the dangerous blade edge, and outputs radar chart to warn the operator. (3) The real-time road condition is transmitted by CMOS image sensor in front of the device, which is convenient for manual operation. Figure 9 shows the control flow chart of the module.

4.3 Icing detection module

The module consists of temperature sensor and CMOS image sensor. The ice surface temperature is measured by the temperature sensor, and the image of the leaves after snow removal is captured by CMOS camera and sent back to the upper computer in real time. The upper computer uses opencv computer vision library to preprocess the image gray and filter, and then uses the significance detection to delete the noise information, so that the recognition result is not interfered, so as to get a more accurate icing image, and then adaptive The threshold is binarized, and Canny operator is used to detect the ice edge and ice cracks. Finally, the image threshold variance is calculated to determine whether there is icing. If so, send a message to the operator for the next action. Figure. 10 shows an effect picture of the image processing process.

4.4 Transducer switch module

The specific process of ultrasonic transducer switch is as follows: after connecting 12V power supply, the DC 12V voltage is raised to AC 220V by the inverter boost module. The single chip microcomputer
controls the on-off of AC through yyac-2 thyristor trigger switch module, which is connected at low level and disconnected when set at high level. The silicon controlled module is connected with several 120W ultrasonic generators. Each generator can be connected with two 60W and 40KHz ultrasonic transducers. A total of eight ultrasonic transducers are provided to work at the same time. The workflow is shown in Figure 11.

![Figure 11 transducer switch module diagram](image)

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