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Research on rapid de-icing intelligent device and its control technology based on multi-machine synergy

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abstract

In this study, a rapid de-icing intelligent device and its control technology based on multi-machine synergy are developed for the ice-covering problem of high-voltage transmission lines caused by global climate change. The current de-icing technology suffers from high energy consumption, difficult engineering application, and constraints of range and stability. This intelligent device integrates four de-icing modes, namely, rotary, percussive, electromagnetic heating and microwave heating, which can flexibly select de-icing strategies according to the ice state, and improve the de-icing efficiency and adaptability. The introduction of UAV magnetic wireless charging auxiliary system solves the range bottleneck and realises continuous operation at high altitude. Using ultrasonic and infrared ranging multi-sensor fusion, combined with the ESP32 master control unit to build the air-ground cooperative closed-loop obstacle avoidance system, to enhance the safety of operation. The mechanical self-stabilisation module is designed based on the principle of balanced gyro, which reduces system complexity and energy consumption and improves reliability and stability. The research results are of great significance in guaranteeing the safety of power grid, reducing the risk of manual overhead operation, promoting industrial upgrading and energy saving and emission reduction, etc., and providing an efficient and intelligent solution for the de-icing of high-voltage lines.

Keywords: High-voltage Line Ice-covering; Multi-machine Co-operation; Multi-modal De-icing; Magnetic Docking Wireless Charging; Intelligent Control.

1 | Introduction

In recent years, global climate change has led to more frequent extreme low temperatures and snow and ice disasters in winter, and the problem of high-voltage transmission line ice coverage has been aggravated, which seriously threatens the safe operation of power grids. Ice cover may cause line tripping, tower collapse and other accidents, affecting residential life and industrial production, and even disrupting the normal operation of society [1].

In the face of this problem, domestic and foreign countries actively carry out research on de-icing technology for transmission lines. However, the current technology has many shortcomings. Domestic power grid companies commonly used microwave, ultrasonic or electric wire fixtures for local heating de-icing, high energy consumption and limited deployment range, it is difficult to cope with the large area covered with ice [2]; universities and scientific research institutions, although in the laboratory on the robotic arm crawling or stand-alone de-icing technology has been researched, but has not yet been achieved in engineering applications. Some foreign teams use UAVs to carry infrared heating or laser equipment to de-ice, which can respond quickly, but are constrained by range, operational stability and obstacle avoidance ability, and cannot be promoted on a large scale [3]; domestically, it is mostly limited to UAV data acquisition and monitoring, and the air-ground co-operative de-icing system is not yet mature. This study focuses on the development of intelligent devices and control technologies for rapid de-icing of high-voltage lines based on multi-machine cooperation, in order to overcome the problems of existing de-icing technologies.

In terms of technological innovation, this research result has outstanding highlights. Firstly, it integrates four de-icing methods, namely rotating, knocking, electromagnetic heating and microwave heating, and with the help of intelligent recognition module, it can make flexible decisions according to the ice state, which significantly improves the de-icing efficiency and adaptability. Second, the introduction of UAV magnetic wireless charging assistance system, the robot can automatically request for replenishment when the power is insufficient, to achieve continuous operation at high altitude, breaking the range bottleneck. Third, the ultrasonic and infrared ranging multi-sensor fusion programme, combined with the ESP32 master control unit, builds a closed-loop obstacle avoidance system with air-ground coordination to enhance operational safety. Fourth, the design of mechanical self-stabilisation module based on the principle of balanced gyro reduces the system complexity and energy consumption, and improves the reliability and stability of the device.

From the viewpoint of social value, the research results are of great significance. It can effectively reduce the risk of power outage caused by line ice-covering in ice and snow disaster-prone areas, safeguard residents' electricity consumption and industrial production, and maintain social stability. Intelligent cooperative operation reduces manual overhead operation and reduces safety risks [4]. Its results can also be expanded to multiple fields of intelligent operation and maintenance market, promote the industrialisation of de-icing equipment, and create new economic growth points. Moreover, the intelligent de-icing system has low energy consumption and high efficiency, which is in line with the national energy saving and emission reduction policy and has good economic and environmental benefits.

2 | Literature Review

Foreign power system robot research began in the 1980s, only a few developed countries such as Japan, the United States and other countries can produce power-carrying operation robots, and most of them are used for the usual inspection line use, do not have the function of de-icing [5].

For the transmission line de-icing robot is still relatively few such products in the world, only Canada has related products in the press. Canada's CIGELE and LIMA laboratories have been in the international leading position in the study of ice-covering, and the construction of ice simulation laboratory, high-pressure laboratory, ice and weather numerical simulation laboratories, with strong de-icing of scientific research power [6]. 2000, Canada's Hydro-Québec Research Institute of Serge Montambault et al.

developed a successful name HQ In 2000, Serge Montambault et al. from Hydro-Québec Institute developed a remote-controlled de-icing vehicle called HQ LineRover, which is the earliest de-icing robot available. The robot can move along power lines or overhead grounding lines, and de-icing is mainly carried out by a de-icing tool mounted on the line rover [7].

However, the robot is too large in mass and complex in structure, and it can only clear the ice cover between two towers, does not have the function of crossing the barrier, and is limited to working on the power line between two towers. In China, especially in the western mountainous areas, the terrain difference is large, the transmission line distance is relatively far, the device is not suitable.

Domestic research on overhead power line robots started late, only in the patrol stage has achieved some milestones. Shandong University, Wuhan University and the Shenyang Institute of Automation of the Chinese Academy of Sciences in the national "863" programme funded by the 110KV, 220KV and 500KV overhead transmission line automatic inspection robots were researched, and made good progress [8]. These inspection robots are able to cross the line accessories, towers and other obstacles, the implementation of a wide range of long-time line inspection operations, although a certain amount of research results have been achieved, but there is still a gap from the practical stage.

From the above research results achieved at home and abroad, it can be seen that the overhead power line inspection robot technology without obstacle-crossing function is more mature and has nearly reached the practical stage. However, China's research on de-icing robots, for the time being, is still in its infancy, and no mature products have appeared [9][10].

3 | Technical programme

3.1 System composition and workflow

The drone first carries the robot to the overhead line, the robot traces along the line and uses infrared to measure the temperature of the high voltage line, after the measurement is completed, the data will be fed back to the operator, who will judge the ice condition accordingly and manually select the de-icing method for de-icing. The robot executes the command to start de-icing, in the process of de-icing, the ultrasonic module and the infrared module determine whether to encounter obstacles, such as encountering obstacles will be fed back to the operator and the drone, the drone carries the robot for obstacle avoidance, after the completion of obstacle avoidance, the drone leaves and the robot continues to run. At the same time, the ESP32 power monitoring module will read the battery power, when the power is less than 20%, send a low battery warning to the drone, the drone starts the portable wireless charging device and hovers above the robot, the robot receiver module receives the energy and starts to charge the supercapacitor, which supplies power to the robotic system after the energy storage is completed.

3.2 Multi-machine synergistic rapid de-icing device

The drone is equipped with an ultrasonic obstacle avoidance module that senses the environment in real time, together with a buzzer and ESP32 controller to form a closed-loop obstacle avoidance system to ensure precise navigation to the ice-covered area in complex terrain. The de-icing device is equipped with a rotary de-icing device that generates friction cutting force by rotating alloy drills at high speed, combined with electromagnetic heating coils that use eddy current effect to melt the overlying ice in a non-contact manner, and a microwave device that accelerates the process of melting ice through molecular resonance. The MG955 servo-driven double-pendulum arm of the ground-knocking robot generates high-frequency impact force to break the thick ice layer, and the infrared temperature gun and Bluetooth module are used to build a temperature feedback network to monitor the temperature of the wire in real time and dynamically adjust the de-icing strategy. The wireless charging technology ensures the continuous operation of the equipment, and the central control system integrates the digital twin to predict the changes of ice conditions, optimise the operation path and power distribution of multiple machines, forming an intelligent closed loop of "environment perception - collaborative ice breaking - performance feedback", which significantly improves the de-icing efficiency and safety of the operation.

3.3 De-icing unit

3.3.1 | Knockout de-icing device

The knockout de-icing device has a central shaft as its core, with two joints (for flexible movement. The key to the device is the MG955 servo attached to the central shaft, which serves as a power and control source, enabling precise control of the angle and speed of rotation.

When the MG955 servo is activated, it drives the active pendulum arm to swing, which in turn transmits force through the driven pendulum arm. The hammer moves with the swing of the pendulum arm, ultimately creating a striking action to remove the ice.

The design of the entire device makes full use of the precise control capability of the servo and the flexibility of the robotic arm, enabling accurate tapping operations in three-dimensional space, and is suitable for de-icing tasks in industrial automation, robotics and other fields.

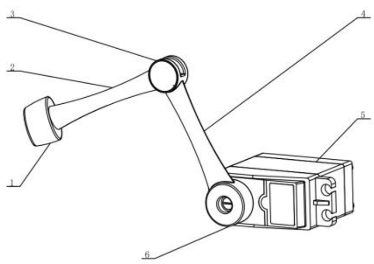

Figure 1 Knockout de-icing device diagram

In terms of structure, this knockdown de-icing device consists of six key parts, corresponding to the serial numbers on the picture (as shown in Fig. _): 1. Knockdown hammer 2. Slave pendulum arm 3. Rotating shaft 4. Active pendulum arm 5. MG955 servo 6. Active shaft. Each part carries out a specific function and works together to fulfil the de-icing task.

3.3.2 | Rotary de-icing unit

The motor drives the rotating parts to rotate at high speed, using friction, impact and cutting forces to scrape or break the ice from the overhead line.

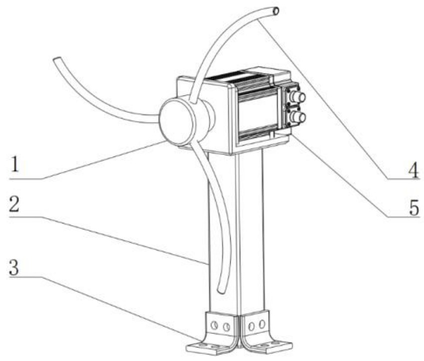

Figure 2 Rotary de-icing device diagram

Structural parts: 1. drive box 2. support column 3. bottom mounting bracket 4. control box 5. electrical connector. The motor provides rotating power, and the transmission system transmits the power to the de-icing parts to ensure smooth and efficient power transmission. De-icing parts: The rotating de-icing head scrapes the ice layer through high-speed rotating centrifugal force, and the de-icing cutter or plough knife can scrape the ice layer more effectively. The suspension mechanism suspends the de-icing device on the overhead line, and the support structure supports the other components. Control system: the control circuit controls parameters such as motor start, stop and speed.

3.3.3 | Electromagnetic heating de-icing device

This electromagnetic heating de-icing process consists of four main steps. First, a spiral tube-type coil (S1) is installed on the power cable as the transmitter of electromagnetic heating. Next, the power cable is judged to be ice-covered or not (S2), and one of them is selected as the excitation frequency by analysing the inherent frequency of the power cable. Then, this excitation frequency is applied to a spiral tube-type coil (S3), thereby generating a guided wave in the power cable. As the guided wave propagates through the power cable, it generates heat due to the principle of electromagnetic induction, which in turn melts the overlying ice. Finally, it is determined whether the removal of the ice cover is complete (S4), and if so, the entire electromagnetic heating de-icing process is completed.

The whole process utilises the principle of electromagnetic induction, which is an efficient and safe method of de-icing by generating guided waves and generating heat on power cables to melt the overlying ice.

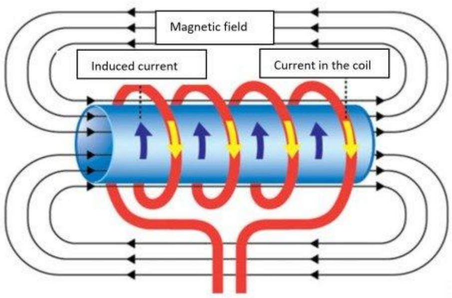

Figure 3 Induction heating schematic diagram

3.3.4 | Microwave heating unit

Then, using the principle of microwave electromagnetic induction, between the anode and cathode electron emission generated microwave electromagnetic field, ice water molecules absorb microwave energy vibration heat, temperature rise melting ice. Microwave heating de-icing process: obtain the initial temperature and humidity of the transmission line environment, determine whether the conditions are met, control the pulley sliding and heating device work, continuous heating until the ice layer melts, to achieve automatic control.

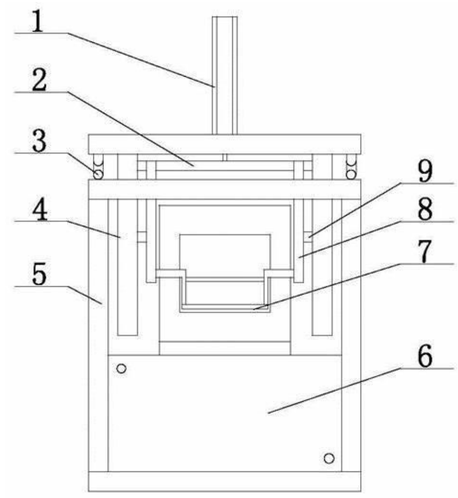

Figure 4 Microwave heating device diagram

The operating principle of microwave heating and de-icing units is based on the interaction between microwaves and the material being heated. When microwave energy is fed into the interior of the furnace, they generate a strong electromagnetic field inside the heated material. This electromagnetic field causes rapid vibration and friction of polar molecules (e.g. water molecules) in the heated material, which generates heat. This heat build-up leads to the melting of the ice, which leads to de-icing. The insulation layer serves to reduce heat loss from the outside of the furnace, allowing more microwave energy to be used to heat the material being heated.

3.4 Barrier avoidance devices

In high-voltage line de-icing operations, UAVs often need to travel through complex environments, and obstacle avoidance is crucial. In this study, an obstacle avoidance system based on ultrasonic module, buzzer and ESP32 is adopted to ensure the safety of UAV flight. The workflow of this obstacle avoidance system is clear and divided into four key stages.

(1) Ultrasonic Transmission Stage

The ESP32 is programmed to control the transmitter side of the ultrasonic module to generate an ultrasonic signal of a specific frequency. The signal travels through the air in the form of sound waves with a certain amount of energy and direction.

(2) Ultrasonic reflection and reception stage

When the emitted ultrasonic signal encounters an obstacle (e.g., a utility pole) during its propagation in the air, part of the ultrasonic energy will be reflected back by the surface of the obstacle. The reflected ultrasonic signal propagates in the direction opposite to the emitted path and is finally received by the receiving end of the ultrasonic module. The sensitive element at the receiving end converts the reflected ultrasonic signal into a corresponding electrical signal and transmits the signal to the ESP32 for processing.

(3) Distance Calculation Stage

When the ESP32 receives the reflected back electrical signal, it records the time interval (i.e. round trip time) that the ultrasonic wave has travelled from transmission to reception. According to the propagation speed of ultrasonic waves in the air (about 340m/s), the total distance travelled by the ultrasonic waves can be calculated. Since this total distance is the distance travelled by the ultrasonic waves round trip, the distance from the actual obstacle to the UAV is half of the total distance travelled.

(4) Judgement and reminder phase

The ESP32 compares the calculated distance with the pre-set safe distance threshold. If the distance is less than the safety distance threshold, it means that the distance between the UAV and the obstacle is too close and there is a risk of collision. At this point, ESP32 will control the buzzer to sound an alarm to alert the operator or trigger the UAV's automatic obstacle avoidance procedure.

Through the above principle and workflow, the "Range + Alert" system based on ultrasonic module, buzzer and ESP32 can detect whether there is an obstacle in front of the UAV in real time and issue an alert when the distance is too close, thus realising the effective obstacle avoidance function of the UAV carrying the de-icing device.

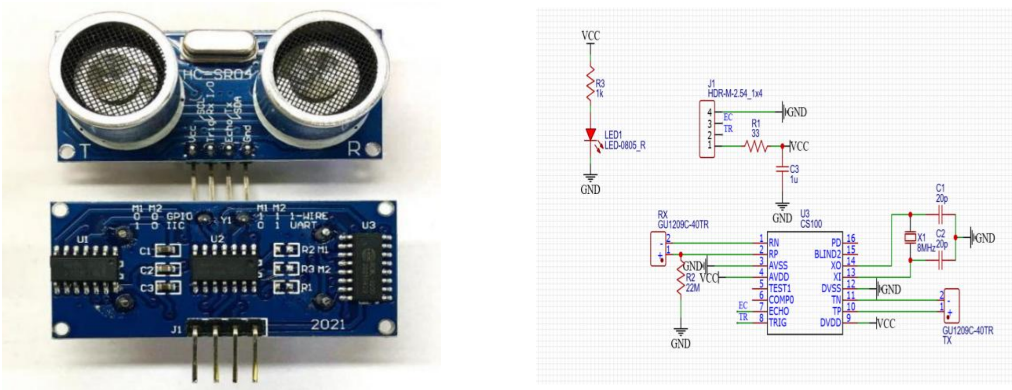

Figure 5 Ultrasonic distance measuring device and circuit diagram

As a sound prompting device, when an obstacle is detected to be too close, the buzzer will emit sounds of different frequencies or patterns according to a preset logic to remind the operator or trigger the corresponding obstacle avoidance action.

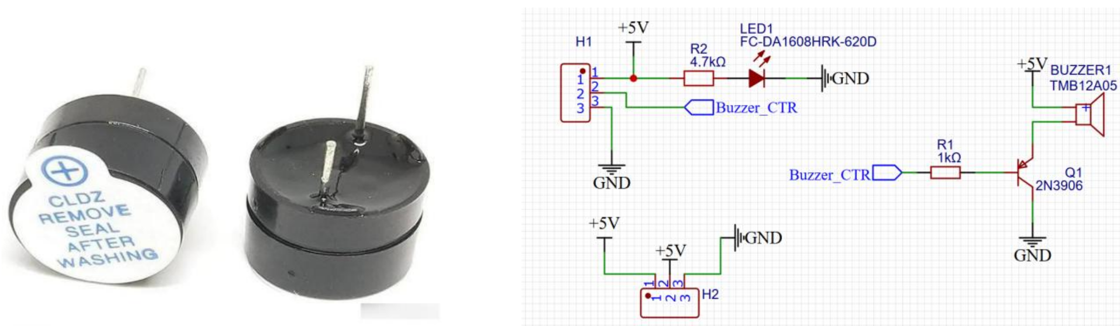

Figure 6 Buzzer device and circuit diagram

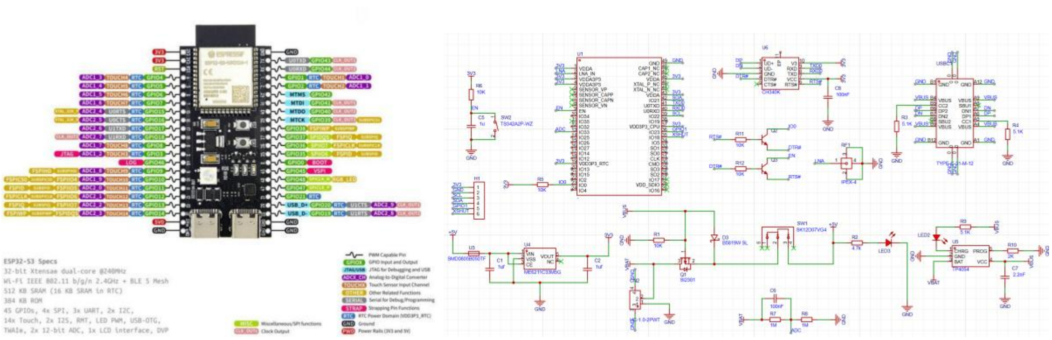

Figure 7 Master ESP32 circuit diagram

ESP32, as the core control unit of the whole system, is responsible for coordinating and managing the work between various modules. Specifically, it is programmed to achieve the control of the ultrasonic module, including transmitting ultrasonic signals, receiving and processing echo signals, etc.; at the same time, based on the calculated distance information and preset thresholds, it determines whether it is necessary to trigger the buzzer alarm or take other obstacle avoidance measures.

3.5 Other devices

In addition to the obstacle avoidance device, the intelligent de-icing system also contains temperature measurement device, balancing device, magnetic suction docking wireless charging device and feedback system, the devices work closely together to ensure that the de-icing operation is carried out efficiently and safely.

1. Temperature-measuring device: It adopts the principle of active thermal radiation measurement by emitting thermal radiation of specific wavelengths and calculating the temperature by using the thermal radiation energy reflected back from the overhead line. This non-contact measurement method can quickly and accurately obtain the surface temperature of the overhead line without affecting its normal operation, providing key data support for judging ice conditions. In practical application, the temperature measurement device can work stably on both thin frost and thick ice-covered lines, providing an accurate basis for the formulation of subsequent de-icing strategies.

2. Balancing device: the core component is the balancing gyro, whose internal gyroscope monitors changes in the attitude of the de-icing device in real time. When the device is tilted due to wind, line slope or its own movement, the gyroscope quickly captures the changes and transmits the data to the control system. Accordingly, the control system calculates the adjustment strategy, commands the brushless motor to adjust the flywheel rotation state, generates inertia force to offset the external interference, and restores the device to balance. The application of the balancing gyro greatly improves the stability and safety of the de-icing device operating on the overhead line, and ensures that the de-icing operation is carried out accurately and efficiently.

3. Magnetic docking wireless charging device: the robot is equipped with a power monitoring function, which automatically sends a request for replenishment to the drone when the power level falls below a set value. The UAV carries a magnetic wireless charging module, and after receiving the request, it quickly flies to the target location, and automatically adsorbs and charges. This non-contact autonomous replenishment method avoids frequent manual intervention or the trouble of returning to the base for charging, significantly improves the system's endurance and autonomous management capability, and enables the de-icing operation to be carried out continuously at a high altitude, which significantly improves the work

efficiency.

4. Feedback system: The temperature sensor monitors the temperature of the high-voltage line in real time and converts it into an electrical signal, which is transmitted to the Bluetooth module. The Bluetooth module converts the electrical signal into a wireless signal and sends it out through low-power Bluetooth technology. The mobile phone installs the corresponding application, receives and analyses the signal, and displays the temperature information in the form of charts, figures or alarms. With the help of mobile phone application, users can remotely monitor the temperature of high voltage line in real time, find abnormalities and take measures in time to ensure the safe and stable operation of the power system, which realises the efficient remote monitoring of the temperature of high voltage line.

4 | Innovation Advantage

In the field of high-voltage line de-icing technology, the intelligent device of this research has made a series of key innovative breakthroughs, showing significant advantages in improving de-icing efficiency and ensuring operational safety, as follows:

1. Multimodal de-icing fusion

The device integrates four types of de-icing means, namely, rotary, tapping, electromagnetic heating and microwave heating. For different types of ice, the operator can manually select the appropriate de-icing method, which is applicable to all kinds of ice-covered conditions from thin frost to thick ice. This multimodal integration breaks through the limitations of a single de-icing technology and significantly improves de-icing efficiency and adaptability to complex ice-covered environments. Compared with the traditional single de-icing technology, it can remove ice of different thicknesses and hardnesses more quickly and effectively, providing a more reliable guarantee for the safe operation of high-voltage transmission lines.

2. Equipped with a wireless charging assistance system for drones

The de-icing robot has a built-in power monitoring function that automatically sends a request for recharging to the drone when the power level falls below a set threshold. The UAV is equipped with a magnetic wireless charging module, and after receiving the request, it can precisely fly to the target position, automatically align and adsorb with the robot, and carry out the charging operation. The system realises non-contact autonomous energy replenishment in the high-altitude operation environment, which greatly improves the endurance capacity and autonomous management level of the system. It avoids frequent interruptions of operation or returning to the ground for charging due to insufficient power, ensures that the de-icing operation can be carried out continuously and efficiently, and effectively improves the overall work efficiency and the consistency of task execution.

3. Equipped with multi-sensor fusion obstacle avoidance system

The system integrates ultrasonic sensors and infrared ranging module, which can measure the distance between the obstacle in front and the line in real time.The ESP32 master control unit comprehensively determines the type of obstacle based on the data collected by the sensors. When a potential danger is detected, on the one hand, a buzzer is controlled to alert the operator; on the other hand, the obstacle information is fed back to the mobile phone and the UAV via WiFi. In addition, the UAV can assist the robot to further analyse the type of obstacle and plan the navigation path, forming an intelligent obstacle avoidance system with air-ground coordination. This multi-sensor fusion and air-ground co-operation greatly improves the safety of the device operating in complex environments and effectively avoids collision accidents.

4. Adoption of the "Balanced Tourbillon" mechanism

The "Balancing Tourbillon" lowers the centre of gravity of the system below the axis of rotation by means of an alloy counterweight, which generates a self-recovering moment by means of the difference in gravitational potential energy. When the device is tilted at an angle of $\leq 15°$, it can be automatically corrected without external energy. At the same time, a damper is used to suppress the inertia of the oscillation and reduce the device's shaking. In addition, the micro-servo motor is equipped to achieve $\pm$ 5mm dynamic counterweight compensation, which further optimises the balance performance of the device and reduces the overall energy consumption. The structure can still maintain the base anti-tilting ability in case of power failure, which ensures the stability of the device in all kinds of working conditions and improves the accuracy and reliability of de-icing operations.

5 | Conclusion

Focusing on the problem of high-voltage transmission line ice-covering, this study has successfully developed a rapid de-icing intelligent device and its control technology based on multi-machine synergy. By integrating four types of de-icing methods, namely, rotating, knocking, electromagnetic heating, and microwave heating, and combining with the intelligent recognition module, the de-icing efficiency and adaptability to different ice layers are effectively improved. The introduction of the UAV magnetic wireless charging assistance system solves the range problem and realises continuous operation at high altitude. The use of multi-sensor fusion obstacle avoidance system and mechanical self-stabilisation module based on the principle of balanced gyro enhances the operational safety and device stability. In terms of social value, the research results play an important role in guaranteeing the safety of power grids, reducing the risk of manual overhead operation, promoting the upgrading of the smart grid operation and maintenance industry, and realising energy saving and emission reduction.

However, with regard to the coordination of multi-mode de-icing coupling, the control of energy consumption and de-icing rhythm of the four de-icing modes need to be further optimised to prevent mutual interference. The reliability of some aerial components in extreme environments needs to be improved, for example, the performance of some sensors and mechanical components may be affected under severe conditions such as ultra-low temperature and strong wind. Future research will focus on optimising the multi-mode de-icing co-operative control algorithm to improve the cooperation precision between the de-icing modes and reduce energy consumption. At the same time, it will also be committed to research and development of aerial work components that are more adaptable to extreme environments, adopting new materials and designs to enhance the reliability and stability of the components under harsh conditions, further improving the intelligent de-icing system and enhancing its comprehensive performance in complex environments.

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References

[1] Li Q, Chai Z, Yao R, et al. Investigation into UAV Applications for Environmental Ice Detection and De-Icing Technology[J]. Drones, 2024, 9(1): 5.

[2] Nampoothiri K N, Bobji M S, Sen P. De-icing device with self-adjusting power consumption

and ice sensing capabilities[J]. Journal of Microelectromechanical Systems, 2020, 29(4): 562-570.
[3] Liu W, Chen Y, Hou F, et al. Fixed spray type anti-ice deicing control system design[C]//Journal of Physics: Conference Series. IOP Publishing, 2019,. 1423(1): 012066.
[4] Zhang Z, Zhang H, Yue S, et al. A review of icing and anti-icing technology for transmission lines[J]. Energies, 2023, 16(2): 601.
[5] Yi Q, Zhuang H, Lu C, et al. Optimal control algorithm of working speed of deicing robot based on fuzzy PID[C]//2020 IEEE 4th Information Technology, Networking, Electronic and Automation Control Conference (ITNEC). Networking, Electronic and Automation Control Conference (ITNEC). IEEE, 2020, 1: 2118-2122.
[6] Bahrami A, Yan M, Shahidehpour M, et al. Mobile and portable de-icing devices for enhancing the distribution system resilience against ice storms: preventive strategies for damage control[J]. preventive strategies for damage control[J]. IEEE Electrification Magazine, 2021, 9(3): 120-129.
[7] Solangi A R. Icing effects on power lines and anti-icing and de-icing methods[D]. UiT The Arctic University of Norway, 2018.
[8] Yang G, Jiang X, Ren X, et al. Site experimental study on smart de-icing device based on the de-icing method by the transferred current of bundled conductors[C]//22nd International Symposium on High Voltage Engineering (ISH 2021). IET, 2021, 2021: 236-241.
[9] Kenzhebayeva A, Bakbolat B, Sultanov F, et al. A mini-review on recent developments in anti-icing methods[J]. Polymers, 2021, 13(23): 4149.
[10] Wang Y, Chen Y, Zhong H, et al. Control Methods for Transmission Line De-icing Robot Manipulator[M]//Electric Power Robots: Modeling, Control, and Singapore: Springer Nature Singapore, 2025: 149-181.