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Research control strategy of hot air blower de-icing system for MW wind turbine blade

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Abstract. Aiming at the intelligent control strategy of the hot air blower de-icing technique for wind turbine blades was requirement. A high efficient and energy-economical intelligent control strategy was designed, the control strategy workflow and two intelligent modes were designed, namely pre-heating mode and de-icing mode. Through field de-icing tests, the results showed that the inner temperature of blade tip was around 30℃ when running at pre-heating mode, the blade tip surface temperature was 5℃, which was able to restrain ice formation and supply fundamental heat for de-icing mode. The inner temperature of cavity reached 60℃ for supplying enough heat to de-ice quickly when running at de-icing mode. Compared with the conventional de-icing method, the intelligent de-icing control strategy was saved 80% energy consumption in one icing period, which improved electrical production. The feasibility of the intelligent control strategy was proved and it benefited for further development of wind turbine industry under cold weather conditions.

Introduction

With the rapid development of the global wind power industry, China has become the world's largest country of wind power in the world [1]. The "13th Five-Year plan" pointed out that we should promote the development of decentralized wind power, and to the southern and the central and eastern as the focus [2]. At present, in China's southwest, central and southern and eastern wind power installed capacity increased significantly, however, due to the special geographical and climatic factors such as the low temperature, high humidity and high altitude, making these region wind turbine is more vulnerable to the icing phenomenon [3]. The icing on the blade surface not only severely restricts the mechanical and aerodynamic characteristics of the blade, but also seriously affects the output performance of the blade [4, 5]. According to incomplete statistics, the loss of wind power generation by blade icing is about 1%~10%, while the loss in the harsh environment is as high as 20%~50% [6], and the ice falls off from the blade will also cause a serious hidden danger of high altitude falling [7].

At present, in order to solve the wind turbine blade surface's icing phenomenon, mainly through the following ways: hot air blower de-icing, thermal resistance de-icing, mechanical de-icing, ultrasonic de-icing, coating technology, etc [8-10]. Hot air blower de-icing, a blower and a heating device are installed in the blade root, and the hot air is blown into the inner cavity of the blade to heat transfer with the outside environment, so that the snow melt off, safe operation, simple equipment, easy changing and low cost [11]. Thermal resistance de-icing, electric heating [13,14] by resistance heating layer laid to the leaf surface layer or inner surface or the appearance, the thermal resistance electricity heating melting blade surface icing, has a fast reaction speed and high efficiency, but it cannot replace the damage resistance, and must be added to the lightning protection device, the system is expensive [12]. Mechanical de-icing, rely on the centrifugal force of

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the wind wheel, inertia force when wind turbine emergency stop, vibration of wind turbine, pneumatic blowing ice or expansion pipe, etc., the efficiency of de-icing is low and non planned shutdown is needed [13]. Ultrasonic de-icing program, using Lamb wave and SH wave presented in the ultrasonic to produce the velocity difference on the surface of blade, thus forming the shear stress, to achieve the purpose of removing ice [14]. Coating technology, improving surface temperature by using black paddle, but only the sunny day can gather temperature to melt ice, and high temperature will affect the surface material of the blade, has a low adaptability; spraying the hydrophobic chemical reagent to prevent the rain from freezing has the weaknesses of short action time, large amount and environmental pollution [15].

The above researches mainly focus on the methods of surface of the blade de-icing, but not yet related to the intelligent control strategy of de-icing. Based on the diameter of wind wheel is more than one hundred meters, and the fast rotating of wind wheel causes the heat dissipation of blade surface quickly, so the de-icing process is extreme consumption of energy. Taking the heat blower deicing system as an example in this study, intelligent control strategy is adopted in the de-icing system. When the environment freezes, the de-icing system enters the preheating mode to ensure the temperature of the inner cavity of the blade, and can delay the freezing of the outer surface of the blade. When the wind turbine begins to freeze, the blade de-icing system can quickly heat up to remove the ice on the surface of the blade. When the intelligent control strategy is not used, the de-icing system can be opened directly from the normal mode when the blade is frozen and the wind turbine performance is affected. After the blade icing is completely removed, the de-icing system then switches back to normal mode, the process not only consumes more energy and times to complete the de-icing work, but also affect the normal operation of the wind turbine to a certain extent.

In order to be more efficient and energy-saving to control blade de-icing system, a set of intelligent control strategy is developed based on the hot air blower blade de-icing system. Develop a set of efficient and energy-saving control strategy for the hot air blower blade de-icing system, and design the working flow of the control logic of the system. The double mode control method of preheating and de-icing is put forward, and the corresponding execution logic of the double modes is designed respectively, the control effect of de-icing system was verified by the feedback data of the anti freezing prototype de-icing in the field.

Design of control strategy

The whole process of the control strategy

The object of study is an anti freezing prototype in a wind farm of Guizhou province, model is 2000kw model, and basic parameters are shown in table 1.

The hot air blower de-icing system for blade of wind turbine comprises power distribution cabinet, de-icing control cabinet, blade root control cabinet, blower, heater, temperature sensor, ventilation pipe, baffle, and distribution cables. Each air blower de-icing system is divided into 10kW, 20kW, 30kW three levels, the inner cavity at the outlet of the ventilating duct and the tip of each blade respectively embedded temperature sensor PT100. The root of blade was closed by circular plate, and the blade root control cabinet is fixed on the baffle plate, towards the side of the wheel hub. The blower and the heater were fixed in the inner cavities of the blade root, and the basic structure is shown in Figure 1. The ventilation pipe was laid close to the front web, and from the beginning of the web extended to the tip of blade as 20m and the diameter is 200mm, schematic diagram of pipeline laying in hot air blower de-icing system is shown in Figure 2 (a). The baffle plate was arranged at the outlet of the ventilation pipe, prevent the hot air reflux, tried to keep hot air energy in the inner region between the baffle and the front of the tip, in order to remove the surface of the outer surface of the blade leading edge as far as possible, so the blade can recover the aerodynamic characteristics. The output performance of the blade can reach 80% or more performance of the blade not covered by ice, the local enlarged drawing of the air inlet is shown in Figure 2 (b). The front web and the back web with the front and trailing edge of blade formed a gap at the tip of the blade, when the hot air flow into the inner cavity of the front web and the blade leading edge, the air flow is extruded from the gap and along the gap of the front and the rear webs or the gap of the rear web and blade back to the root of blade, completed the flow field in the whole blade, and the relative position is shown in Figure 2 (c).

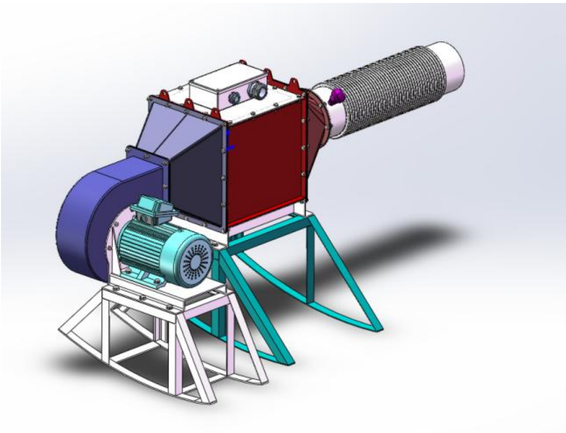
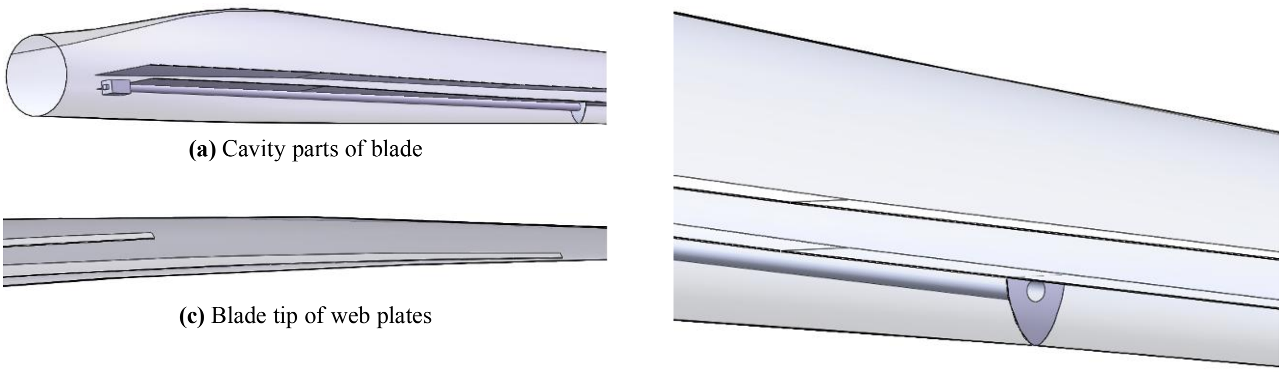


Fig.1. The structure diagram of hot air blower de-icing system

Table 1: Basic parameters for 2000kW wind turbine

Item	Parameter
Power(P)	2000KW
Rotor diameter(D)	115m
Blade quantity	3
Hub height(H)	80m
Velocity(v)	9.2m/s
Survival temperature	-30~45℃
Operating temperature	-20~40℃
Cryogenic restart temperature	-18℃
Freeze-up	2~3months



(a) Cavity parts of blade

(c) Blade tip of web plates

(b) Ventilation pipe outlet

Fig.2. The 3 D diagram of hot air blower de-icing system

The surface of the blade icing must satisfy the following conditions:

1) The high humidity environment, relative humidity is more than 85% RH;

2) The temperature is low; the ambient temperature is T < 2;

When the environment is not up to the freezing condition, the de-icing system is not required to be opened. When the environment is frozen but the unit is not frozen, the pre heating mode of the de-icing system is prepared for the following de-icing work. When the unit frozen is determined, the de-icing mode is opened, based on these, developed a set of intelligent, energy saving, fast feedback control strategy for de-icing system, as shown in figure 3.

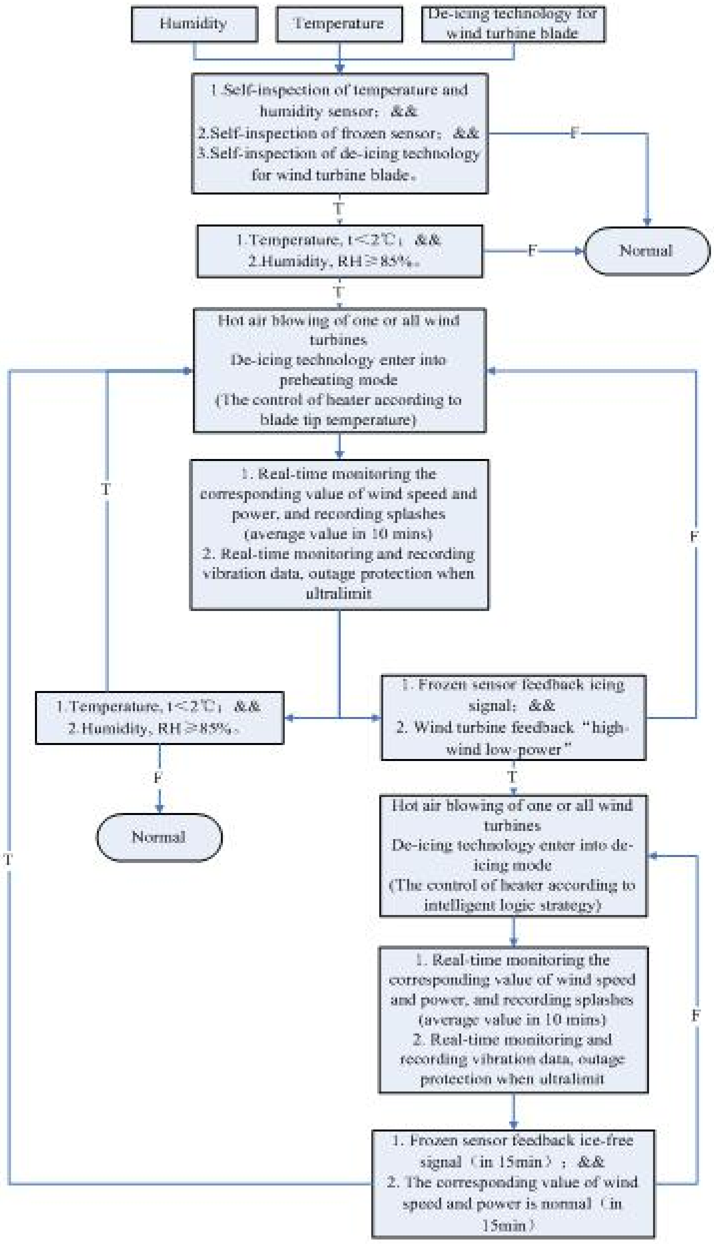


Fig.3. The flow chart of control strategy for de-icing system

When the field ambient temperature T > 2℃ or relative humidity RH < 85%, the environment has not reached the icing condition, the unit works normally, and the hot air blower de-icing system is in a standby state.

When T < 2℃ and RH ≥85%, the environment begins to freeze, because of the characteristics of blade, wind wheel rotation, wind speed and other dynamic factors, the blade surface is not covered with ice just entering the freezing environment, de-icing system opens the preheat mode, the heater is turned on the low block (10kW) to do heat preservation for the inner cavity of the blade, controls the temperature T4 of tip is between 25 and 35 ℃, on the one hand, pave the temperature way for the follow-up de-icing mode, so the system can quickly achieve the specified de-icing temperature; On the other hand, the inner surface of the blade is always maintained in a heat exchange and heat conduction with the outer surface, so can delay the ice on the surface of the blade to a great extent.

When T < 2℃ and RH ≥85%, the freezing sensor located at aft end of engine room feeds back icing signal to the main control of the de-icing system, at the same time, the wind speed and power of the control system is not matched, that is, when the actual power is smaller than the wind speed at this time. At this point, the de-icing system opens the de-icing model, the heater is turned on high gear (20kW), combined with low grade(10kW) to maintain the internal cavity's temperature of the blade T3=55~65℃. The freezing sensor has the function of self heating and removing the ice, when the environment is frozen and then the freezing sensor is frozen, the sensor feeds back icing signal to the main control and turn on the self heating to remove ice from the surface of the sensor.

When the freezing sensor feedback system that there is no icing signal in 15min and the control feedback of the unit is operating normally, that is the wind speed and the power matched, the de-icing system exits the de-icing mode and enters the preheating mode.

When T > 2℃ or RH < 85%, the environment doesn't reach the freezing conditions, the system exits the de-icing mode, and the unit comes back into normal operation mode.

The preheating mode

Preheating mode mainly has the following two kinds of logic control:

1. Temperature control of the blade tip, blade inner cavity uses the PT100 temperature sensor to monitor the temperature of the tip, under the condition of the de-icing system opens the preheating mode, the hot air blower is turned on the low gear (10kW) to delivery of hot gas stream to the inner cavity of the blade. Cavity temperature rises to 30℃ quickly with time, for the existence of heat exchange between the air in the inner cavity of the blade and the heat exchange between the inside and outside of the blade, cavity temperature is not possible to maintain a constant value, therefore, through the control the start and stop of the low gear (10kW) to control temperature is maintained at 30℃ plus or minus 5℃. In Figure 4, the preheating control logic makes the temperature range at the tip will remain dynamic fluctuation of T4=25~35 ℃, so as to form a relatively stable of cavity temperature. When the cavity temperature of the blade tip is maintained at the desired temperature about 30℃, the blade cavity temperature is above 30℃, that is forming a thermal insulation cavity. Test results show that when the blade cavity temperature is kept at about 30℃, at this point through inside and outside air flow heat exchange of the blade, can make the outer surface of the blade to maintain at about 5℃, and thus to a certain extent, to delay the surface of the blade freezing. When the blade is required to open the de-icing mode, in the insulation environment of the blade cavity, the blade cavity temperature is heated from 30℃ to 60℃, while without the preheating mode control strategy, it is required to heat the blade cavity temperature to 60℃ from 0℃. Adopting the preheating mode with intelligent control strategy not only can greatly shorten the de-icing work time, but also can avoid the overheating of the root or the extreme cold of the tip caused by the uneven heating, which caused the rapid aging of the blade material.

2. Time interval control, through the de-icing system to set the heat blower in the preheating mode, heating the blade cavity for 45min every 4 hours.

The time interval logic control mainly is as an aid in the application of temperature feedback control logic, when the temperature sensor at the inner chamber of tip damaged, the de-icing system can continue to provide normal preheating work.

The de-icing model logic

De-icing mode mainly has the following two kinds of logic control:

1. The temperature control of the inner cavity, when the system enters the de-icing mode, the hot air blower is turned on the high gear (20kW), the temperature T3 of the inner cavity is rapidly increased from the preheating environment temperature, when the temperature sensor feeds back T3 is more than or equal to 60℃, the heater switches from high gear (20 kW) to low gear (10kW), the rising slope of T3 decreases. When T3=65℃, the heater is closed and the heating is stopped, then

the temperature inside the cavity begins to drop. When T3 < 60℃, the heater is turned on the low gear (10kW), at this time the drop rate of the cavity temperature slows down. When the T3 dropped to 55℃, the heater is switched from the low gear (10kW) to high gear (20kW), the inner cavity temperature began to rise rapidly until 60℃, continues the above cycle process, so that the blade cavity temperature T3 is always maintained at a dynamic balance of about 60℃, as shown in Figure 5. The experiment results show that the ice of the outer surface is rapidly melted by the continuous heat exchange on the external surface of the blade with inner cavity that the temperature is relatively stable at 60℃. Heat exchange between the inner and the outer surfaces of the blade will introduce losses of the heat flow energy inside the cavity. At the same time, in order to prevent the blade cavity from overheating, it is necessary to switch to the high gear, low gear or turns off the heater, to ensure a dynamic balance of inner cavity temperature range in 60 ± 5 ℃, the logic diagram of de-icing mode as shown in figure 5.

2. Security monitoring, the blower sends hot air to the cavity of the leading edge through the ventilation pipe. In order to avoid the temperature is too high to cause damage to the blade material, when the temperature sensor installed at the outlet of the vent pipe feeds back the temperature is more than 80℃, the hot air blower should immediately stop the heating action to protect the blade.

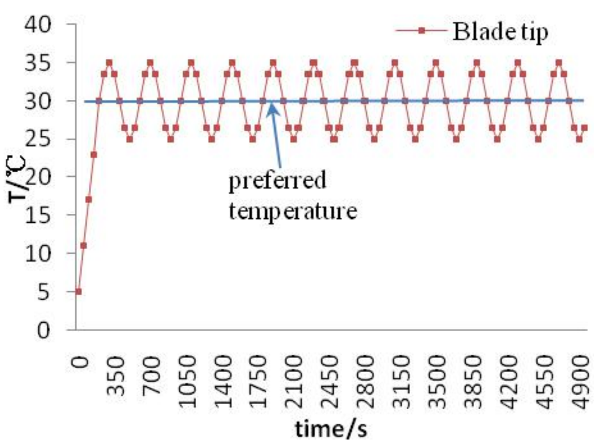


Fig.4. The temperature diagram of blade tip

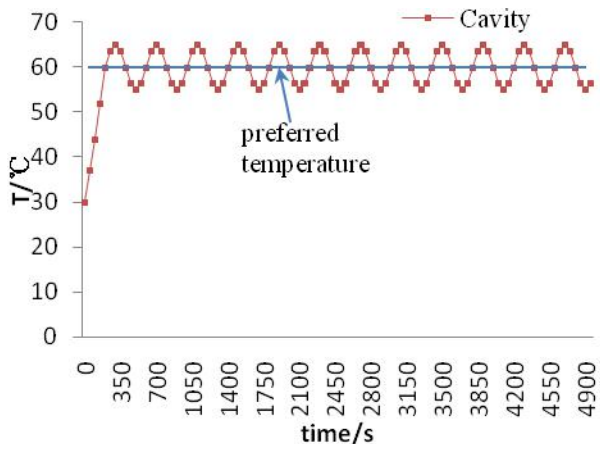


Fig.5. The temperature diagram of cavity

Field test

Figure 6 showed the trend of the inner cavity temperature when de-icing mode was turned on at three blades. T axis represented measured temperature and data was captured in 1600 seconds every 50 seconds. After turning on the de-icing mode, the trend of inner cavity temperature of three blades was similar and increased quite fast. The temperature trend of blade 1 and blade 2 was almost the same, but temperature change of blade 3 was slightly different from that of blade 1 and 2. The difference among three blades might result from the time difference of their start time. At de-icing mode, blade 1 and 2 reached their set value 60℃ at 700s, while blade 3 got to the point at 1300s. According to control strategy, heater was set to switch from 20kW to 10kW and thus the temperature increase speed slowed down. The temperature of inner cavity of blade 1 and 2 reached 65℃ after running de-icing mode for 1500s, and blade 3 reached it a bit late. In summary, based on the measurement data, the temperature of blade inner cavity is able to rise to its set value fast and then enter a stable controlled state.

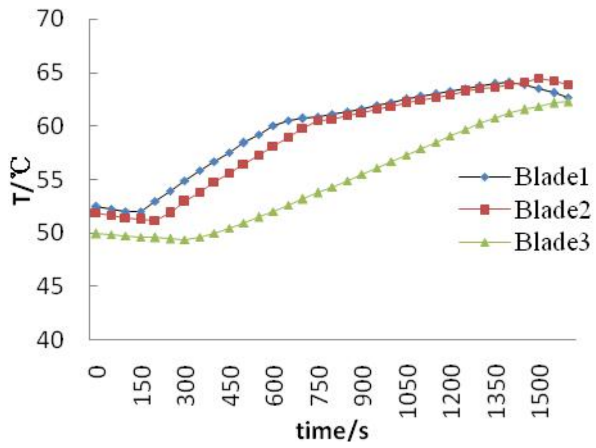


Fig.6. The start-up process under de-icing mode

Figure 7 showed the temperature fluctuation of three blades under stable de-icing mode. The data was captured every 50 seconds in 2800 seconds after the heater entered the stable state. As it showed, the temperature of inner cavity was in dynamic balance, which was always around the set value 60℃. To be specific, the lowest temperature was 55℃ and the highest temperature was 65℃, and the narrow range verified the advantage of intelligent control strategy.

In order to verify the effectiveness of heat mode with de-icing control strategy, the relationship of inner cavity temperature and heat mode was measured. As the temperature change of three blades was almost the same, only the relationship of temperature of blade 1 and heat mode was presented. For simplification (red and violet plots), if one mode was on, it showed 50 in T-axis; if the mode was off, it showed 45 in T-axis. As Figure 8 showed, when the inner cavity temperature was above 55℃, high power mode (20kW) was on and low power mode (10kW) was off; when temperature reached 60℃, high power mode (20kW) was off and low power mode (20kW) was on. Therefore, the slope between 55~60℃ was obviously larger than 60~65℃. When the inner cavity temperature was above 65℃, heater was off and the temperature began to drop quickly. As long as it was below 60℃, low power mode (10kW) of heater was turned on again. If icing condition was so severe that the temperature kept dropping below 55℃, high power mode (20kW) of heater took place of low power mode (10kW). All in all, the intelligent control strategy sustained the heat dynamic balance of the inner cavity temperature via high/low power mode switch.

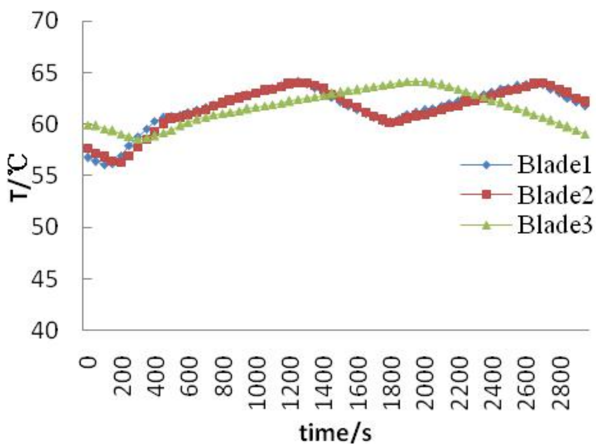


Fig.7. Temperature variation of cavity under de-icing mode

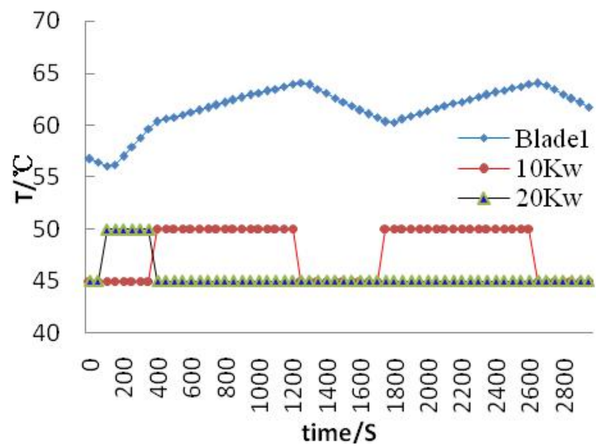


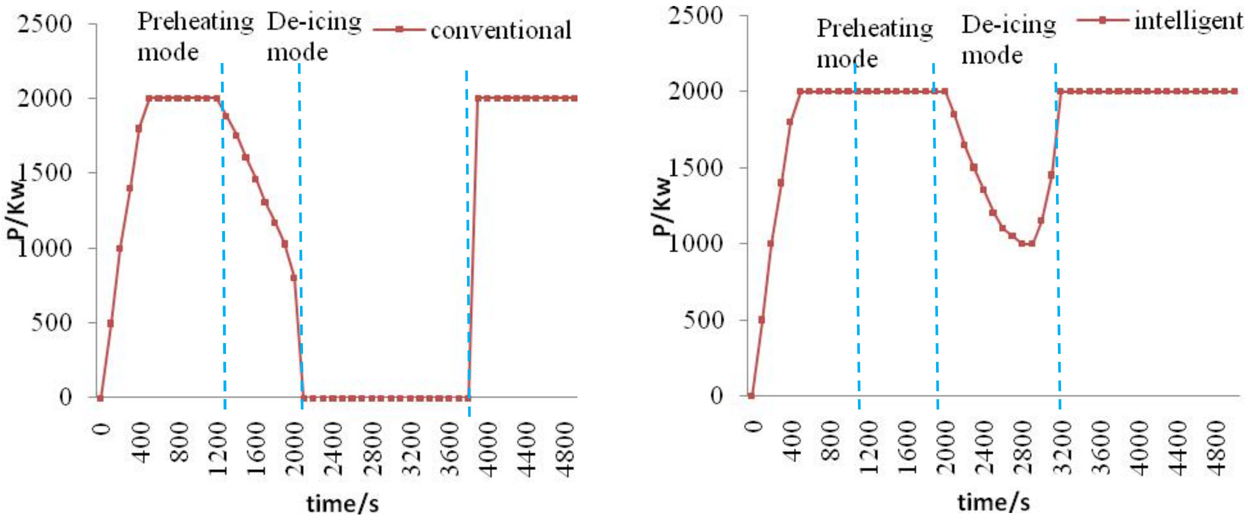
Fig.8. Temperature of cavity correspond with heater gears

The analysis of energy consumption

Figure 9(a)(b) showed the power curve of wind turbine using conventional de-icing method and intelligent de-icing control strategy. As Figure 9(a) shows, when wind turbine operated normally

(0~1200s), output power was nearly 2000kW; when there was ice formation but no heating process on blade surface (1200~2000s), output power decreased quickly from 2000kW to 800kW. With further deterioration of icing on blades, the wind turbine stopped operation as soon as output power was below 800kW (2100~3800s), and thus the output power become zero at this moment. When ice on the blades was removed completely, output power of wind turbine returned to 2000kW (3900~5000s). As Figure 9(b) showed, the output power of wind turbine using intelligent control strategy was about 2000kW when it operated normally (0~1200s). When ice formed in the surroundings (1200~2000s) , wind turbine started to work under pre-heating mode so that the temperature of blade tip and surface was nearly 30℃ and 5℃. Under this circumstance, icing in the surroundings did not affect the output power. At this moment, pre-heat process consumed some energy but electricity was generated in 2000kW. With further deterioration of icing environment, the sensors reflected the condition of icing process on blades and output power decreased to 1000kW. To solve this issue, de-icing process was started, the temperature of inner cavity increased from 30 to 60 ℃ quickly and then kept heat dynamic balance (2100~3200s). As a result, the removal of ice on the blades could be done in 20 minutes with high efficiency. During 3300~5000s, wind turbine operated normally again and thus output power of it returned to 2000kW.

Through the comparison of conventional de-icing method and intelligent de-icing control strategy, the advantage of intelligent de-icing control strategy was as followed: (1) When the environment went into icing conditions, conventional method did not take any actions to protect the blades or sustained the operation of wind turbine. Therefore it lost a large amount of energy production. However, the wind turbine using control strategy consumed a little amount of energy to apply pre-heating mode, but ensure the normal electricity production. (2) When ice formed on the blade surface, conventional wind turbine could not generate electricity as soon as de-icing process started to undertake and the process cost 30 minutes. However, the intelligent wind turbine switched its mode from pre-heating mode to de-icing mode, in which process wind turbine still connected to grid and supplied electricity at its part load condition. The lowest output power was 1000kW and the duration of de-icing was only 20 minutes, which could save more energy compared with the conventional process. In a single cycle of intelligent de-icing process, total electricity consumption K1 included a spot of energy for pre-heat process K11, energy loss and energy consumption for de-icing process K12 and original energy cost of wind turbine K13; in a single cycle of conventional de-icing method, total electricity consumption K2 contained energy loss due to icing on blade at initial process K21, energy loss and consumption when de-icing and original energy cost of wind turbine K23. The quantity of K1 was only 20% of K2, which means the implementation of intelligent control strategy could help save a great deal of energy for wind turbine operation in cold weather conditions.



(a) conventional de-icing wind turbine (b) intelligent Logic control de-icing wind turbine

Fig.9. The power curve of wind turbine under conventional de-icing method and intelligent de-icing control strategy

Conclusion

Based on hot air de-icing system, an intelligent control strategy was developed which included pre-heating mode and de-icing mode. Two modes had different strategies and made the de-icing process more smart, more intelligent and more quickly. The data captured in the field tests verified the feasibility of the control strategy and the consistency between the expected effect and real reaction.

1) The hot air de-icing system turned on its pre-heating mode to sustain the temperature of blade tip as 30℃ and the temperature of blade surface as 5℃ when the surrounding environment was freezing but the blade had no ice on it. The pre-heat process restrained ice formation on blade surface and also supplied certain heat for later de-icing process.
2) According to the field measurement, when de-icing mode was turned on, the temperature of inner cavity rose quickly. When it reached the expected value 60℃, heat power switched between 10kW and 20kW by intelligent control strategy, ensuring the inner cavity temperature fluctuate at 60±5℃. The de-icing process brought operation safety to wind turbine and high efficiency to de-icing process, and further proved the feasibility of the design of intelligent control strategy.
3) Hot air de-icing system applied smart control strategy and thus in one de-icing cycle, its energy consumption was only 20% compared with conventional de-icing method. It confirmed that the intelligent control strategy was much more energy-economical and high-efficient than conventional de-icing methods.

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