Analysis of upper air detection above frozen wind turbine in high-altitude mountains

Tao Feng[1,2,*], *Jun* Guo[1,2], *Li* Yang[1,2], *Zelin* Cai[1,2], *Bo* Hu[1,2], and *Zhou* Jian[1,2]

[1]State Grid Hunan Electric Power Corporation Limited Disaster Prevention & Reduction Center, 410129, Changsha, China
[2]State Key Laboratory of Disaster Prevention and Reduction for Power Grid Transmission and Distribution Equipment, 410129, Changsha, China

Abstract. In winter, icing is one of the key factors that restrict the generation of wind power in high-altitude mountains. In this paper, through analyzing the upper air temperature profile of wind farms by using microwave radiometer, we established the water drop temperature calculation formula under non-phase change conditions. Three vertical temperature structures conditions and the relationship between ground water drop temperature and icing efficiency under different conditions are analyzed. This study makes up for the deficiency that the wind turbine icing numerical prediction model can only give the three-dimensional ambient temperature, but cannot give the icing efficiency, which will improve the prediction accuracy of wind turbine icing.
Keywords: Frozen wind turbine; Microwave radiometer detect; Upper air temperature; Icing efficiency.

1 Introduction

As one of the most frequent transmission line icing disasters countries, China has experienced more than 1,000 icing disasters on power grids with voltage levels of 66kV and above, since the icing disaster of power grid equipment in China occurred in 1954. With the development of renewable energy, wind power, photovoltaic, etc. are playing more important roles than before in electricity production. However, Wind farms always build in high-altitude mountains, which are facing icing disasters on transmission lines and wind turbines in winter. This icing disaster could lead to serious power outage or irreversible damage to turbines. For instance, on 16 December 2020, more than 90% of wind turbines in Hunan, China were frozen due to the extreme cold weather, which causes a wide range of power outages. Moreover, during 15-18 February 2021, a serious power outage caused by freezing rain occurred in Texas, United States, due to the lack of anti-freezing admixture and heating components when extremely cold weather landing. Thus, the icing on wind turbines is one of the most serious problems faced by renewable energy in winter.

---

[*] Corresponding author: njuftao@126.com

Many researchers who focus on wind power forecasts neglect the icing factor when predicting the wind power since the wind farm locating on the plain. However, icing is the main problem for wind farms in winter.

At present, the research of wind turbine icing calculation is based on experiment analysis or numerical model. Experiment analysis mainly focuses on studying the icing and aerodynamic characteristics of the icing wind turbine under different conditions, and calculate the power loss[1, 2, 3]. In addition to conducting tests in the laboratory, Shu et al analyze the loss of wind power after icing through the natural environment test and established the power loss prediction model[4]. However, due to the obvious difference between the experimental results in the laboratory and the actual environment, it is difficult to use the model directly in the icing prediction business of the wind farm. Moreover, the icing model of the wind turbine in the natural environment is affected by the local terrain and weather characteristics. Its application scope is limited. The numerical method can be used to calculate the icing of a large range of wind turbines under different conditions, which provides an idea for the icing prediction of a large range of wind farms[5, 6, 7]. While all of the relative models are based on the ground meteorological conditions. In fact, the temperature of ground-water drops is affected by the characteristics of the temperature profile in the upper air. Before calculating the wind turbine icing, it is important to establish the relationship between the temperature of super cooled water on the ground and upper air temperature.

This essay will analyze the result of a wind farm upper air temperature detection data, and then build a quantitative model, which could simulate the relationship of the temperature between upper-air and ground water droplets. This model could also calculate the temperature of super cooled water on the ground, thereby determining the efficiency of icing on the ground.

2 Methodology

2.1 Introduction of detection instrument

The microwave radiometer retrieves the temperature, humidity and liquid water in air profile by receiving atmospheric microwave radiation, infrared radiation and meteorological parameters such as ground temperature, humidity, and air pressure.

The vertical observation range of the microwave radiometer is from the ground to 10,000m, with a total of 58 layers of data. In the 0-500m section, the resolution is 50m; In the 500m-2000m section, the resolution is 100m; In the 2000m-10000m section, the resolution is 250m.

Table 1. Resolution of Microwave radiometer.

Range	0-500m	500-2000m	2000-10000m
Resolution	50m	100m	250m

2.2 Process of detection

The detection site is located in the Xuefeng Mountains with an altitude of 1385m, Xiaoshajiang Town, Longhui County, Shaoyang City, Hunan Province. The average annual icing duration time exceeds 60 days. The detection area covers 9000 ㎡, close to a wind farm, which is out of supply in the winter icing period.

During 3rd-7th Jan 2018, the detection site experienced cold processes, the relative humidity keep 100% in the whole process. From the night of 3rd Jan 2018 to 4th Jan 2018, the detection site raining slightly, and the rain is proved as freezing rain by observation. After 4th Jan 2018 20:00, the rain became lighter and changed into drizzle till to the 5th Jan 2018 early morning, when the rain stopped. From 5th Jan 2018 to 8th Jan 2018 morning, the weather was dominated by heavy fog, with drizzle on 6th, the visibility below 200m. At 10:30 on 8th Jan 2018, the weather turned to sunny, the process went to an end.

2.3 Analysis for measurement parameter

On 4th-5th Jan, the ground temperature is from -2°C to 1°C; On 6th-8th Jan, the ground temperature dropped and changed to -6°C to -1°C. The inversion layer existed in the entire process. In the beginning, the maximum temperature of the inversion layer rose from 5°C on 4th Jan to 8°C on the 6th Jan steadily, and the maximum temperature remained at 500m to 1000m height. On 7th Jan, the inversion layer weakened rapidly, the maximum temperature was less than 2°C, and the height was less than 500 meters.

The change of precipitation and inversion layer along with the change in the thickness of the icing on the transmission line. Hence, the detection focused on the icing thickness on the simulated transmission line, the precipitation of the detection area and the upper air inversion layer.

During the daytime of 4th Jan, the icing type on the simulated line was glaze, with 2mm thickness ice. As the accumulated precipitation, the ice thickness on the simulated line increased, grown to 3mm by 19:00. The ice type was observed at 9:00 5th Jan as hard rime, the main component was the glaze. In the afternoon, the ice on the transmission line began melting because of the increasing ground temperature. During the next process, owing to the non-precipitation weather, the ice type on the simulated line was rime. On 7th Jan, there was 1.5mm ice on the simulated line that remained all day. After 8th Jan, the ice on the simulated line melted with the weather turned sunny.
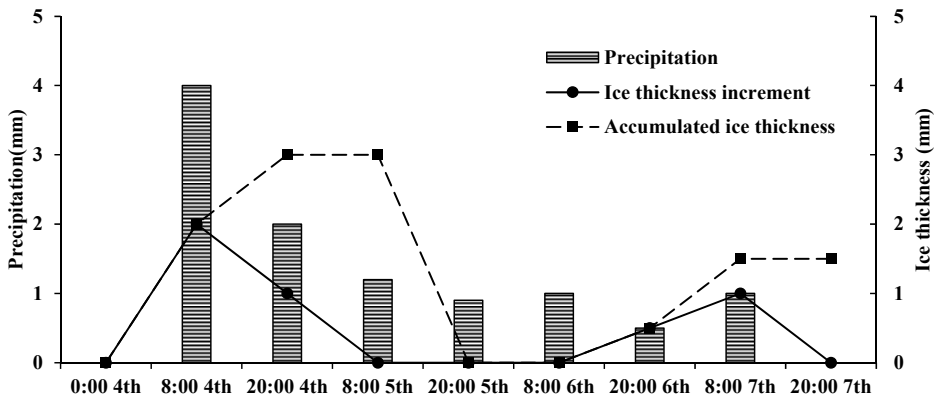
Fig. 1. .Precipitation, ice thickness increment and accumulated ice thickness from 0:00 on 4th Jan to 9:00 on 8th Jan.

3 Calculation for freezing raindrop temperature

3.1 Formula

In the procedure of upper air droplets fall to the ground, the droplets have heating exchange with the surrounding air. In order to calculate the temperature of the super cooled droplets,

this detection applies microwave radiometer to detect the air temperature from 0°C upper air to the ground and then use the formulas below to calculate the temperature of droplets in different layers. Due to the process had no transformation in droplets phase change, formulas do not consider the heat loss in phase change.

$$dT=dQ/C_w \cdot m \tag{1}$$

$$dQ=WStdT \tag{2}$$

$$t=dH/V \tag{3}$$

Here, dT is the change of droplets temperature, dQ is the heat of the exchange, W is the heat exchange coefficient between droplets and air, which equal to $30W/m^2 \cdot °C$, C_w is the specific heat capacity of water, taking 4217 $J/kg \cdot K$, m and S are the mass and surface area of droplets, t is the moving time of droplets between two adjacent layers, dH is the distance between two adjacent upper air layers, V is the falling speed of droplets. Based on a previous study, the diameter of droplets is about 0.5mm, and the falling speed is about 4m/s according to the raindrop spectrum[8].

3.2 Analysis of examples

Three different periods in the freezing rain process were chosen, they are ground icing was grown rapidly period(10:00 4th Jan), icing maintenance period(19:00 4th Jan), and icing grown slowly(19:00 6th Jan).

At 10:00 4th Jan, the warm layer which temperature is above 0°C locating between 1800m and 200m. In the warm layer, the air temperature is closed to the temperature of the water drop, indicating that the water droplets completely absorb the air heat. Below 200m, the air temperature is lower than 0°C, the temperature decrease by 1.5 °C per 100m. Since the observed ice thickness is equal to 60% of the total precipitation, it means that the temperature is not low enough, and the precipitation is not completely covered by ice.

Similarly, at 19:00 4th Jan there is a warm layer in the upper air, but the ground temperature rises near 0°C, and the icing thickness does not change, indicating that there is no super cooled water on the ground, and the icing increase efficiency is 0. At 19:00 6th Jan There is also a warm layer in the upper air, but the ground temperature decreases to -4 °C, and the height of the cold layer decrease to 100m. The temperature gradient reaches 4 °C per 100m. The precipitation changes into icing rapidly, and the icing conversion efficiency is 100%.
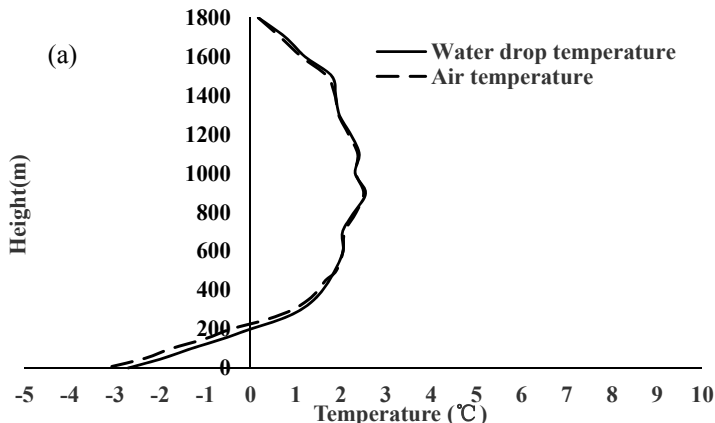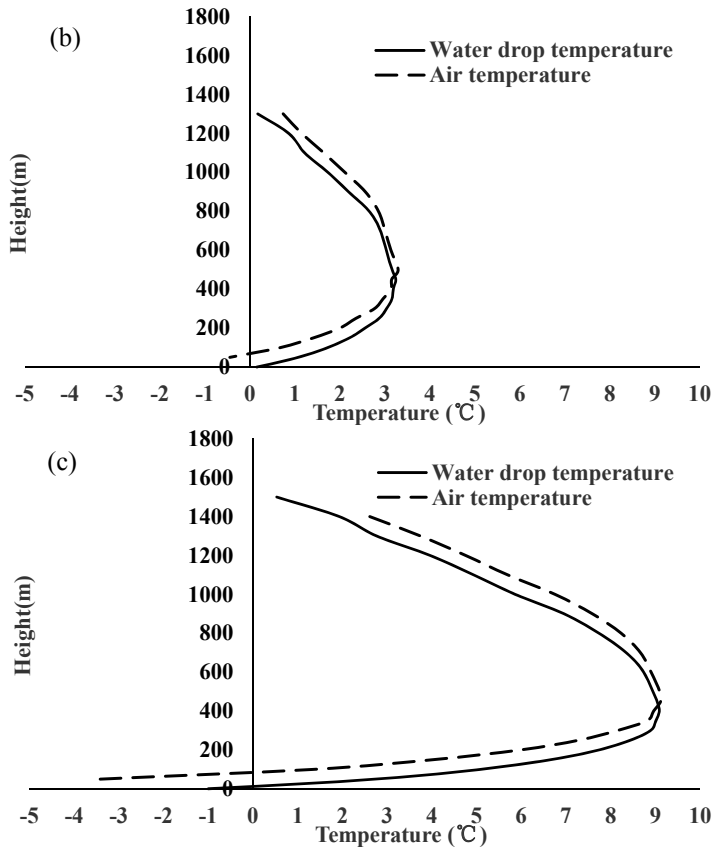
Fig. 2. .Profile of water drop temperature and air temperature at (a) 10:00 on 4th Jan. (b) 19:00 on 4th Jan. (c) 19:00 on 6th Jan.

4 Conclusion

This paper analyse the wind turbine icing in different type of vertical temperature profile through microwave radiometer detection. Based on the analysis, the relationship between the ground icing efficiency and the temperature is established and will help improve the wind farm icing predicting model. The main conclusions are as follows:

(1) There exists an area which a temperature higher than 0°C in the upper air when freezing happened. The area contains a lot of liquid water droplets

(2) When the water droplets fall to the ground, the icing efficiency is determined by ground temperature. When the ground temperature is below -3°C, the efficiency of water freezing in droplets is high, the icing increases quickly. However, when the ground temperature is between -3 to -0.5°C, the efficiency is 60% due to insufficient super cooling of the water droplets.

This essay only considers the heat exchange during freezing rain without phase change. In fact, the phase change influence heat absorption when the water droplets fall onto the ground. Therefore, future research is to analyze more data in the freezing rain and freezing fog process with phase change. Finally, acquire a more accurate mathematics relationship between upper air and ground icing efficiency when rime happens.

Acknowledgments

References

1. S., Dierer, R., Oechslin, and R., Cattin. Wind turbines in icing conditions: performance and prediction. Adv. Sci. Res., 6, 245–250, (2011)

2. Xu Xiaomin, Niu Dongxiao, Wang Peng, et. al., The weighted Support Vector Machine based on hybrid swarm intelligence optimization for icing prediction of transmission line. Math. Probl. Eng., 2015, 1-9, (2015)

3. Davis, N., Hahmann, A. N., Clausen, N-E., et. al., Forecast of icing events at a wind farm in Sweden. J. Appl. Meteorol. Climatol., 53(2), 262-281, (2014)

4. Shu Lichun, Li Hantao, Hu Qi, et. al., Effects of ice degree of blades on power losses of wind turbines at natural environments. Proceedings of the CSEE, 38(18), 5599-5605, (2018)

5. Li Jingrui, Teng Yun, Hui qian, et. al., Wind turbine output prediction model considering numerical weather forecast, High Volt. Eng., 44(2), 61-65, (2018)

6. Kosovic B, Haupt SE, Adriaansen D, et. al., A comprehensive wind power forecasting system integrating artificial intelligence and numerical weather prediction, Energies, 13(6), 1372, (2020)

7. Rustem Manatbayev, Zhandos Baizhuma, Saltanat Bolegenova, et. al., Numerical simulations on static Vertical Axis Wind Turbine blade icing, Renew. Energ., 170, 997-1007, (2021)

8. Gao Wende, and Zhao Chang, The shape and terminal velocity of the falling raindrops, Phy. & Eng., 29(6), 65-70, (2019)