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Research to the influence factors on shedding processes of three-types icing

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ABSTRACT

Based on observations of 30 wire icing cases and meteorological elements at four meteorological stations in Hubei Province from 2009 to 2016, the influence of ice properties, meteorological conditions, and shortwave radiation on different ice shedding processes in three-types of ice was studied. It was found that ice melting and mechanical ice breaking is the main mechanisms causing the shedding of ice, with no ice sublimation in the mountainous areas of China. Ice mainly shed off during 08:00–14:00 h, with a shedding duration of 1–5 h. The ice shedding rate increased slowly with a rise in temperature less than −3 °C, while it increased quickly when the temperature ranged from −3 to −1 °C. The maximum wind speed in the shedding period was greater than that during the preceding 6 h in 86.7% of icing cases, indicating that wind had a significant effect on the shedding of soft rime ice. Incoming shortwave radiation was much higher on ice shedding than non-ice shedding days, especially the hourly value, which either reached or approached the maximum value in 76.7% of all icing cases. The maximum value of shortwave radiation had a strong correlation with the maximum value of the ice shedding rate in hard rime and mixed ice, with the correlation coefficients reaching 0.83 and 0.69, respectively. With an increase in the maximum value of shortwave radiation, the increase in the ice shedding rate was larger for mixed ice than hard rime ice.

1. Introduction

Freezing rain in the plains and freezing drizzle/supercooled fog in mid-high altitude mountain areas are the main types of disaster weather that causes icing on wires (Makkonen and Ahti, 1995; Ikeda et al., 2007; Zhou et al., 2012). With its relatively short duration, freezing rain has a strong rainfall intensity, leading to a large ice density. Freezing drizzle and supercooled fog have a longer duration than freezing rain, and therefore have a weaker rainfall intensity or even no precipitation, resulting in a smaller density of ice. For all types of ice, large-scale icing processes that occur in populated areas or in areas where outdoor equipment is used will have catastrophic effects. An extensive freezing rain and snow disaster in January–February 2008 affected up to 20 provinces in southern China, with a direct economic loss greater than 151.65 billion yuan. It severely affected transportation, energy supply, power transmission, agriculture, and resident's livelihoods (Ding et al., 2008; Farzaneh, 2008; Zhou et al., 2009; Niu et al., 2012). However, large-scale icing disasters are not common in plain areas. The low temperature and abundant water vapor in mid-high altitude mountain areas make them prone to icing disasters in winter (Lamraoui et al., 2014; Neil et al., 2014). There is a dense network of transmission lines in these areas and wire icing disasters have attracted the attention of power departments and scholars.

Ice types can be categorized into glaze ice, rime ice, and mixed ice. There have been many studies of the factors influencing the different icing processes, such as their temporal and spatial distributions (Zhang, 1991; Li et al., 2008a, 2008b; Wang, 2011), role of atmospheric circulation (Tao and Wei, 2008; Zhang et al., 2008; Zhao and Sun, 2008; Zhou et al., 2009), meteorological elements (Zerr, 1997; Sundin and Makkonen, 1998; Lu et al., 2000), stratification characteristics (Rauber et al., 2000; Thériault et al., 2006; Zhou et al., 2017), the influence of cable diameter (Druez et al., 1999; Chao et al., 2011), and micro-

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physical conditions (Yuter et al., 2006; Chen et al., 2011; Niu et al., 2012). Glaze is more common in the south than in the north, while soft rime is more common in the north than in the south, with both being more common in mountains than plains in China (Zhang, 1991; Wang, 2011; Wang, 2014). The number of icing days have gradually decreased in the past 50 years, but their intensity has increased significantly (Zhao et al., 2010). The frequent intrusion of cold air and large amounts of water vapor brought into China by atmospheric circulation anomalies are the key elements in large-scale icing events (Li et al., 2008a, 2008b; Ye et al., 2009). A full study of meteorological factors such as temperature, relative humidity, wind speed, wind direction, and precipitation in glaze and rime ice formation has indicated that glaze ice requires more significantly rigorous meteorological conditions than rime ice, while mixed ice requires the loosest meteorological conditions (Bernstein, 2000). The freezing rain formed by the melting process requires a specific height, thickness, and temperature for the near-surface cold and warm layers (Rauber et al., 2000), with the result that glaze ice mainly occurs in the plains and is less frequent than the other types of ice. The conditions for the formation of freezing drizzle by the warm rain process are not strict in the cold and warm layers. It is often accompanied by rime ice in mountainous areas, making the occurrence of mixed ice more frequent, which seriously threatens the safe operation of transmission lines and communications towers (Gultepe et al., 2014).

In wire icing, the surface of the wire is frozen by supercooled liquid droplets. The changes in physical parameters, such as the number concentration, average diameter, and liquid water content determine the icing intensity. The rainfall intensity of freezing rain is a key factor that affects the intensity of glaze ice, with its droplet spectral characteristics being similar to those of stratiform cloud precipitation (Chen et al., 2011). The water content of supercooled fog determines the intensity of rime ice, with its fog droplet characteristics similar to those of advection fog (Niu et al., 2012). Wind is also an important factor that determines the extent of in-cloud icing. There must be wind to move the supercooled liquid droplets to a wire. The icing rate is proportional to the product of wind speed and the liquid water content of supercooled fog. Savadjiev and Farzaneh (2004) found that the effect of wind speed on ice growth is stronger during in-cloud icing than that during precipitation icing. The occurrence of freezing drizzle can significantly promote the rapid growth of mixed ice, but it is more effective in the wet scavenging of fog droplet diameter greater than 12 μm (Zhou et al., 2016). Based on an in-depth analysis of the physical mechanisms that occur in the icing process, Makkonen (1984, 2000) proposed an icing model that considered the characteristics of collision rate, capture rate, and freezing rate of supercooled droplets. This model can describe the variation in ice thickness, and has been accepted by many researchers.

However, while the model can effectively simulate changes in ice thickness, it simulates the actual ice thickness by calculating the contribution of supercooled droplets, and therefore cannot accurately determine the onset of ice shedding. It usually indicates that icing is initiated when the temperature is less than 0 °C, with the occurrence of freezing rain or supercooled fog, and indicates that icing ends when the temperature is above 0 °C. The determination of icing occurrence is usually accurate, as low temperatures and large amounts of droplets are the two decisive conditions for icing, and an icing event could be assumed to occur when wind speeds measured by heated and unheated anemometers exceed a certain limit (Parent and Llinca, 2011). However, it is unreasonable to determine the ending of the icing process only by temperature because ice shedding is usually caused by three processes of ice melting, ice sublimation, and mechanical ice breaking, and not all of them require a temperature greater than 0 °C (Druez et al., 1995). Ice shedding can cause the power line to bounce up and down, which is sometimes called sleet jumping. Mechanical ice breaking is an important hazard and causes damage to power lines. Ice breakage and shedding will lead to unbalanced power line tension, which will cause a series of secondary disasters such as line disconnection, flashover, damaged fittings, and collapsed towers (Kollar and Farzaneh, 2013). This type of ice shedding is the result of many factors, such as atmospheric conditions, and the properties of ice accretion and icing duration, which is a complex dynamic and thermodynamic process. In previous studies, to reduce the threat to power line operation safety caused by ice-shedding, researchers have mainly simulated the dynamic characteristics of ice-shedding processes on different kinds of transmission lines using the finite element method (Kálmán et al., 2007; Kollar and Farzaneh, 2008; Murín et al., 2016). However, there have been relatively few studies of dynamical-thermal meteorological conditions and radiation characteristics of ice shedding, and these are even more scarce in China. Thus, an understanding of the various rules and mechanisms influencing the ice shedding characteristics in different ice types are even more limited.

Based on icing observation data from four conventional meteorological stations in mid-high altitude mountainous areas of Hubei Province, we conducted a study to objectively classify different icing cases, identify the three types of ice shedding, and analyze the mechanisms by which ice shedding is initiated. Finally, the effects of ice properties, meteorological conditions, and radiation characteristics on the shedding processes of hard rime, soft rime, and mixed ice (mixture of glaze and rime) were assessed. The results will improve our understanding of the whole icing process, including the formation, growth, maintenance, and shedding periods in mid-high altitude mountainous areas. They will also strengthen the monitoring and early-warning of severe secondary disasters such as line disconnection, and tower collapse caused by unbalanced line tension in the case of ice shedding. A scientific basis was developed for the relevant government departments to manage icing disasters in mountainous areas.

2. Field observations and methods

2.1. Field observations

In the winter of 2008 and 2009, comprehensive observations of test-cable icing and the macro-microphysical characteristics of fog and precipitation were conducted at Enshi Radar Station (Es; 30°17′N, 109°16′E; 1722 m a.s.l.), Jinsha Station (Js; 29.63°N, 114.21°E; 751 m a.s.l.) and Dacaoping of Shennongjia (Snj; 31.63°N, 110.33°E; 2593 m a.s.l.) (Jia et al., 2010; Niu et al., 2012; Zhou et al., 2014). In the winters from 2012 to 2016, in cooperation with the China Electric Power Research Institute, consecutive field observations on test-cable icing were conducted at Es, Js and Shennongding of Shennongjia (Snj; 31.45°N, 110.31°E; 3100 m a.s.l.). A total of 30 complete test-cable icings with duration above 24 h were observed. As shown in Fig. 1, the four observation stations are located in mid-high altitude mountainous areas in the southwest, southeast, and west of Hubei Province, respectively, which are the three major heavy icing regions in Hubei Province (Zhou et al., 2013; Huang et al., 2015). The southwest and southeast regions have a dense distribution of transmission lines from the Gezhouba Power Plant, Three Gorges Power Transmission Project, and the West–East Power Transmission Project, and both regions are influenced by cold air and warm moist air, whereas Shennongjia in the west is representative of an icing area in a high altitude mountainous area.

Field observations included photographs of ice and measurements of ice thickness, ice weight, cloud cover, weather phenomena, and meteorological elements. The experimental installation consisted of non-energized test cables, an automatic weather station (temperature and humidity probe), heated anemometer, and camera. To ensure that wind speed data were available during icing periods, the heated anemometer (model 05103) was used to observe the wind speed during icing events. The ice on the anemometer was removed from time to time during heavy icing periods. There were only a few hours during the observations when the anemometer was frozen. We conducted icing observations at the national basic meteorological stations in Enshi, Xianning, and Shenongjia, which were located at the base of mountains.