Cold Regions Science and Technology 148 (2018) 131–141

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

A new atmospheric icing detector based on thermally heated cylindrical probes for wind turbine applications

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ARTICLE INFO

Keywords:
Atmospheric icing
Wind turbine
Cold climate
Wind energy

ABSTRACT

This paper presents a new method to detect atmospheric icing conditions using different arrangements of thermally heated and instrumented cylindrical probes. The proposed method offers a new low-cost alternative to detect icing conditions. A mathematical model describing the heat transfer behaviour of each probe has been developed and validated experimentally in a temperature-controlled wind tunnel. *In situ* measurements under icing conditions have shown great potential for the detection of the onset, the duration and the intensity of an icing event.

1. Introduction

In a world where sustainable development has become of prime importance, several countries have recently decided to diversify their energy sources and have invested into wind power generation. For example, Canada's installed capacity went from 689 MW in 2005 to more than 11,000 MW in 2017 (CanWEA, 2016). However, wind turbines are not yet fully adapted to all environments. As an example, nordic countries face problems related to the production of wind energy in cold climate (CC), where icing is a major obstacle to the reliable production of electricity using wind turbines (Davis, 2014; Ilinca, 2011; Battisti, 2015; Kraj and Bibeau, 2010). Ice accumulation on the blades alters the aerodynamic profile causing underproduction and/or stoppage of turbines, which can result in important financial losses (Gillenwater, 2008; Ilinca, 2011; Kraj and Bibeau, 2010). Lacroix recently predicted annual cold climate wind energy losses of more than 2TWh for Canada, which represent 5% of the country's total annual wind energy production (Lacroix, 2013). Laakso et al. (2010) reported that, from December 11th 2007 to the end of April 2008, Sweden suffered an estimated 5% loss in energy production due to icing (Laakso et al., 2010), which correlates with Lacroix's estimation. Moreover, Gillenwater observed that mean energy production losses could reach 20% during ice-prone periods (2008). Atmospheric icing is a complex meteorological phenomenon that usually leads to a non-uniform accretion on the structures. In turn, uneven accumulation increases the loads sustained by the blades and other mechanical elements that ought to be designed accordingly. Fatigue related problems, caused by icing, were observed (Homola, 2005) and are to be taken seriously when wind turbines are installed in CC. To counteract the adverse effects of CC, ice prevention systems, such as electrothermal and hot air heating systems, are nowadays being offered to clients by major turbine manufacturers such as Enercon, Siemens, Nordex, Senvion and Vestas (Sloth, 2012; Jonsson, 2012; Bolduc, 2015; Sachse, 2017; Frolund, 2017; Roloff, 2017; Nielsen, 2017). One drawback of those systems is that they require a substantial amount of energy to operate (*i.e.* couple of hundred of kW for MW turbines), which decreases the overall efficiency of the wind turbines. Mayer (2007) reported that an electrothermal system designed for a Vestas V80 would consume approximately 82 kW, which represents 13.7% of the power generation of the wind turbine at 8 m/s. Another electric heating system was tested on a small Bonus 150 kW mk III and it consumed on average 1.7 kW (Pinard and Maissan, 2003). From 2004 to 2006, at Olostunturi, in northern Finland where harsh icing conditions prevail (up to 100 days per year) the energy consumption of a blade heating system was estimated to be 3.5–5.5% of the annual energy production (Laakso et al., 2010). As highlighted by Laakso et al. (2010), a reliable ice detector is an essential part of a blade heating system since an incorrect detection or a malfunction can lead to either excessive or insufficient heating. It is therefore undeniable that precise and reliable ice measurement information (*i.e.* onset of icing, icing severity, duration, accumulation and persistence) is crucial to operate wind turbines equipped with ice prevention systems. Likewise, wind turbines not equipped with such systems and operating in CC would also benefit from the use of reliable and accurate ice detectors. For such operating mode, icing detection can be used to stop the turbine in order to protect the various mechanical elements (*e.g.* gearbox, bearings, main shaft, blades…) against increased loads caused by ice accumulation. As any complex phenomena, wind turbine icing is not yet very well understood (Kraj and Bibeau, 2010), but it has been

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https://doi.org/10.1016/j.coldregions.2018.01.009
Received 31 July 2017; Received in revised form 19 January 2018; Accepted 23 January 2018

postulated that proactive actions, such as setting the turbine at standstill or at idle during an icing event (*i.e.* early stopping), might reduce the amount of ice accumulated on the blades. It has been shown that early stopping strategies can be effective means to cope with the adverse effects of icing when no ice prevention systems are used, but these strategies must rely on accurate icing measurement (Nelson, 2014; Nielsen, 2017; Battisti, 2015). During an ice storm, when the turbine is running, ice accumulates on the blades at a higher rate than on a stationary structure, due to the relative velocity of the moving surfaces (*i.e.* the blades) with respect to the ice crystals present in the environment. This suggests that turbines should be stopped during icing events to prevent excessive accumulation. However, revenue losses caused by early stopping are major issues for wind farm operators since they are counting on the fact that a strategically stopped turbine will become available sooner after the icing event, thus leading to potential, but uncertain, financial gains. Based on nacelle mount ice detection, Nelson (2014) showed that, in eastern Canada, production could be increased by approximately 18% by proactively shutting down and avoiding large ice build-up on the blades. Also in eastern Canada, Trudel (2014) implemented early stopping strategies based on weather forecast instead of local measurement of icing. However, he was not able to systematically improve the annual energy production, in part due to the uncertainty in the forecast models used. These results suggest that early stopping strategies can be beneficial, but reinforce the need for accurate and reliable ice detectors on each turbine. Finally, it is also important to detect and quantify icing on wind turbines for health and safety purposes. Shed ice can present a serious threat to workers and civilians (*e.g.* hikers, cross-country skiers, snowmobilers) who find themselves in the vicinity of an iced wind turbine. Alarms can be triggered when ice is present on the turbines to inform the operating personnel, and nearby passers-by, that ice projections are at high risk. In such situations, turbines can be stopped to prevent ice throw, therefore addressing important health and safety issues. Since icing events have an important impact on the income of a wind farm, being able to identify precisely the conditions encountered on potential sites would be very helpful before making important investments. Reliable ice detection devices would be very valuable for site assessment.

2. Ice detection techniques: state of the art

Ice detectors for wind turbines can be divided in two categories: nacelle based approaches and blade based approaches (Cattin and Heikkilä, 2016). This section presents the principal ice detection methods and instruments for both approaches.

2.1. Nacelle based approaches

2.1.1. Double anemometry

One of the most popular nacelle based techniques is called double anemometry. This ice detection method, presented in detail in a patent owned by General Electric (Ormel et al., 2009), consists in using a heated and an unheated anemometer to infer the presence of icing. This method relies on the fact that the behavior of the unheated anemometer is affected by icing, while the heated anemometer is not. Icing is thus detected when a difference of speed is measured between the two anemometers. The main drawback of this technology is that a small film of ice is not enough to make a significant difference in the measured speed (Laakso et al., 2010), hence leading to an incubation period that can last for hours. Moreover, the method can be sensitive to low temperatures effects, for example, a negative error, without the presence of icing, has been observed between the two anemometers (Parent and Ilinca, 2011). It has also been reported that it can be difficult to set a minimal threshold error, associated thereafter to icing, due to the unpredictable effect of icing on the behavior of cup anemometers (Laakso et al., 2003b). Nevertheless, based on our experience and on private communications with operators and developers, double anemometry is fairly easy to implement and can be used as a good indicator of icing occurrences.

However, this detection method:

- does not yield the exact beginning of an icing event due to the extended incubation period;
- cannot be used to detect the end of an icing event;
- cannot be used to infer the intensity of an icing event.

2.1.2. Combination of meteorological measurements

Another nacelle based method consists of a combination of relative humidity and dew point measurements to infer icing conditions. Leine Linde Systems IPMS offers such a system that is also equipped with a 360° camera to verify the ice accumulation in real-time (Cattin and Heikkilä, 2016). A relative humidity greater than 95% and a temperature lower than 0 °C are the conditions usually used to determine when icing is occurring. However, the validity of this method is yet to be proven, since it was observed that 33% of the icing events observed between October 1999 and April 2002 at Pori in Finland occurred when the relative humidity was less than 95% (Laakso et al., 2003b). It has been reported that visibility and cloud base height can also be used to detect in-cloud icing (Parent and Ilinca, 2011). However, this technique also presents some drawbacks as cloud base height and visibility information might not be readily available and thresholds might be site dependent.

Even though these two methods (double anemometry and combination of meteorological instruments) are relatively easy to implement when all the measurements are available, they do not allow the user (*e.g.* wind turbine operator) to instantaneously obtain all the needed information about ice formation. In order to fully assess and adequately measure the various parameters associated with icing (start, end, duration, intensity, persistence), numerous ice detectors have been developed, tested and used on wind turbines. Here is a short description of the the principal nacelle based ice detectors used in the wind energy industry.

2.1.3. Saab Combitech - Ice Monitor

This detector consists of a rotating vertical cylinder that measures the weight of the accumulated ice. While this sensor measures directly ice accumulation, Wickman (2012) has reported several problems such as 1-snowflakes agglomerating on the cylinder, which can result in false detections; 2-formation of ice near the bearings that can affect the sensor response; 3-the ice detector is sensitive to vibrations and is limited in precision (± 50 g). Finally, Cattin and Heikkilä (2016) have reported that because it was originally designed to detect high loads, this sensor cannot detect light icing events.

2.1.4. Goodrich/Rosemount - 0872F1/0872E3

This detector, designed to measure freezing rain, relies on the change in the natural vibration frequency of a vertical strut to detect the presence of an added mass due to ice accumulation. When the natural vibration frequency shift reaches a given threshold, a heating system is activated to melt the accreted ice and the measurement cycle restarts. The frequency of heating is therefore a good indication of the icing rate and can be used in this manner (Wickman, 2012). Despite the wide use of this sensor in meteorology, it has not been widely adopted in part due to its limited use intended only for glaze/freezing rain conditions. Moreover, it has been observed that false measurements can occur during episodes of heavy rain (Wickman, 2012) and that snowfalls can cover the sensor and hinder the operation of the measuring device (Cattin and Heikkilä, 2016).

2.1.5. Labkotec - LID 3300IP

This detector uses the propagation of ultrasound in a wire bent in an egg shape. When icing occurs, the damping of the ultrasound signal in the wire is increased and icing is detected when the signal reduction