Cold Regions Science and Technology 100 (2014) 36–49

Contents lists available at ScienceDirect

Cold Regions Science and Technology

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

Atmospheric icing impact on wind turbine production

Fayçal Lamraoui [a,c,*], Guy Fortin [b], Robert Benoit [c], Jean Perron [a], Christian Masson [c]

[a] The Anti-Icing Materials International Laboratory, University of Quebec at Chicoutimi, 555, boulevard de l'Université, Chicoutimi, QC G7H 2B1, Canada
[b] Bombardier Aerospace, 2351 Boulevard Alfred-Nobel, Montreal, Qc, Canada
[c] Department of Mechanical Engineering, École de technologie supérieure 1100, rue Notre-Dame Ouest, Montreal, QC H3C 1K3, Canada

ARTICLE INFO

Article history:
Received 22 April 2013
Accepted 19 December 2013

Keywords:
Ice accretion
Wind turbine
Re-analysis
Atmospheric icing climatology

ABSTRACT

Wind turbine performance depends mainly on the wind speed and aerodynamics of blades. The roughness generated from ice accretion can significantly reduce the aerodynamics and consequently the power production of the wind turbine. This study locates the glaze and rime ice on the blade, to detect the critical zones involved in significant power production loss. On the blade, the distribution of the elementary power production as well as the type and thickness of the accreted ice are inconsistent. Under icing conditions, the outer section of the blade starting from the radial position $r/R = 0.8$ contribute significantly to the blades aerodynamics. The freezing fraction is unevenly distributed; since it initially forms rime ice near the root and then glaze toward the tip of the blade. The critical freezing fraction 0.88 associated with the double horn ice shape is spatially limited and occupies a restricted segment on the blade and gradually moves towards the tip with decreasing temperature. With the use of power degradation analogy with sub-scaled rotor blades of a helicopter under icing conditions, a power loss factor is introduced to quantify and locate power loss along the blades of wind turbines. The study is based on four values of liquid water content that delineate five classes of icing severity. Including power loss factor, the most significant power loss that corresponds to freezing fraction 0.88 is found to be located at $r/R \sim [0.93\ 0.96]$ which corresponds to $T = -2.6$ °C, -4.5 °C, -12 °C, and -20 °C and for liquid water content $LWC = 0.04\ g \cdot m^{-3}$, $0.07\ g \cdot m^{-3}$, $0.2\ g \cdot m^{-3}$, and $0.36\ g \cdot m^{-3}$ respectively. The resulted power degradation can reach a maximum of 40%. Locally it is the shape rather than the thickness of ice that causes more power loss, meanwhile when considering the whole blade, power degradation is controlled mainly by ice thickness regardless of the type of ice. The results obtained can help the setup of a sensor that triggers the ice-protection system upon detection of critical freezing fraction.

1. Introduction

Numerous cold climate countries already utilize and will progressively make more use of wind energy, because of their propitious high wind potential. Cold climate regions represent an unavoidable beneficial environment for wind energy. For this reason and in order to maintain maximum extraction of power production, wind turbine manufacturers including blade's airfoil designers are required to accommodate the hazardous conditions of atmospheric icing events. Cold regions with higher altitudes represent the best sites for wind farms; wind speed increases approximately by $0 \cdot 1\ m \cdot s^{-1}$ each 100 m of altitude within the first 1000 m (Parent and Ilinca, 2011). Colder regions are characterized by a potential of wind power 10% higher than other regions, because of their higher air density. Since cold air is denser than warm air, it increases the kinetic energy of wind which leads to further power production of wind turbine (Fortin et al., 2005). Commonly wind turbine farms are located in coastal or mountainous areas; these regions are exposed frequently to icing events during the cold seasons (Tammelin and Säntti, 1998). Besides freezing precipitation, low-level stratus clouds at subzero temperatures and more specifically fog cause serious challenges to land, air and sea transportation and greatly affect the wind turbine industry (Bendix et al., 2005).

Ice accretion on the blade of a wind turbine reshapes the blade airfoil and affects negatively its aerodynamic properties. The damaging effect of atmospheric icing on wind turbine production is not limited to severe icing events and high amount of ice accretion; even small amounts of ice accretion on the leading edge of the blade degrades drastically the aerodynamic characteristics of the blade and consequently the expected electric power (Jasinski et al., 1998; Marjaniemi and Peltola, 1998). Furthermore, icing events affect wind assessment and the performance of wind farms by generating measurement errors, power losses, premature mechanical failures, electrical failure and safety hazards (Parent and Ilinca, 2011; Seifert et al., 2003). Besides load asymmetry, vibration and safety hazards, certain icing conditions may cause significant economic losses for the wind turbines industry.

The occurrences of severe icing events necessitate to set the wind turbine on non-operational mode in order to minimize ice accretion and its aerodynamic effects. In general, without the de-icing or the

---

[*] Corresponding author.
E-mail address: faycal.lamraoui@gmail.com (F. Lamraoui).

0165-232X/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.coldregions.2013.12.008

anti-icing procedures, ice accretion on the blades remains for a significantly longer period than duration the icing event itself (Laakso et al., 2010). Bose and Rong (1990) demonstrated that even a vestige of roughness generated from the smallest ice accretion on a wind turbine blade will weaken the expected wind energy by up to 20%. More precisely, wind energy that is weakened by ice accumulation and duration of icing events encounter power losses that range between 0.005% and 50% of the annual production (Botta et al., 1998; Laakso and Peltola, 2005; Tammelin and Säntti, 1996).

An experimental study achieved by Antikainen and Peuranen (2000) on wind turbine blades showed that icing events that last at least a few hours, generate a mass and aerodynamic unbalance. Furthermore, in case this asymmetrical state persists for a long period (days or weeks), the power production and turbine lifetime drop considerably. A costly anti-icing strategy is used to minimize icing effects; however it is not a practical solution for icing concerns since this strategy can consume approximately 25% of the energy produced by the wind turbine (Makkonen and Autti, 1991).

Previous studies have looked at wind turbine aerodynamics and performance degradation. The investigations and analysis involved the different effects of rime and glaze (Hochart et al., 2008), by analyzing ice accretion effects on lift to drag ratio (Hochart et al., 2008; Jasinski et al., 1998) and power degradation (Dierer et al., 2009; Jasinski et al., 1998). Hochart et al. (2008) analyzed in-fog icing measurements from the Murdochville wind farm in the Gaspé Peninsula (Canada). The study revealed a significant torque reduction located on the outer third of the blades. In order to counterbalance the icing effect on the blade, the active heating system on the blade represents an effective solution (Parent and Ilinca, 2011) that needs further devoted research to lower its cost. Under icing conditions, Dierer et al. (2009) indicated that the anti-icing heating system reduces the loss of the annual power production 3.5%, compared to 10% of annual loss without a heating system. Also, under rime conditions, Jasinski et al. (1998) demonstrated that the performance loss of wind turbine can reach 20%.

In attempting to assess the long term severity of atmospheric icing for wind turbines, Lamraoui et al. (2013) presented the climatology of icing severity for wind turbines, using 32 years (1979–2010) of meteorological data extracted from the North American Regional Reanalysis (NARR).

In general, the severity assessment of icing event depends on the field of application and the targeted problem being considered. The icing severity index introduced by Lamraoui et al. (2013) represents the varying degrees of icing severity that combine different threat factors by weighting each according to a scale of seriousness.

In collaboration with Bell Helicopter, Fortin and Perron (2009) performed an experimental study based on a spinning rotor blade developed at the Anti-icing Materials International Laboratory. The objective of that study is to investigate ice physics, low energy de-icing system and ice-phobic coatings for small helicopters. Compared to a clean blade, the power required to rotate an iced blade increases with decreasing air temperature until reaching its maximum at about 5200 W that corresponds to a critical freezing fraction of 0.88. This critical value is associated with the formation of a double horn ice shape. Beyond the maximum of 5200 W, the required power decreases with decreasing air temperature to reach its minimum at about 1200 W. This minimum power occurs when the blades are clean without ice accretion. The effect of air temperature on power is due to the ice shape change with the freezing fraction which in turn depends on air temperature and liquid water content. The partial freezing of water initiates a water runback that freezes afterward, causing an airfoil reshape and aerodynamic degradation.

With the use of the results of Fortin and Perron (2009), the present study focuses on identifying crucial parameters that control the type of ice accretion on the blades of a wind turbine which causes high power loss such as: Freezing fraction, liquid water content, temperature and the critical radial position on the blade. Typical values of icing events were extracted and calculated from NARR data during a time period of 32 years. The current paper also investigates and attempts to estimate the contribution of each localized zone along the blade of the wind turbine to power losses that occur under different icing conditions.

2. Methodology

The models used for the current study attempt to involve more relevant parameters, in order to improve the assessment of the severity of icing events, and more specifically the production loss of wind turbines caused by ice accretion.

In addition to the liquid water content and the duration of icing events for different icing severity classes involved in the quantification and the assessment of the icing severity index (Lamraoui et al., 2013), the present study focuses on exploring the aerodynamic degradation distribution along the blade, under different meteorological conditions and geometries of the blades. In order to cover a typical range of liquid water contents and various severity classes (Fikke et al., 2006; Lamraoui et al., 2013), the values of LWC 0.04 $g \cdot m^{-3}$ (light), 0.07 $g \cdot m^{-3}$ (moderate), 0.2 $g \cdot m^{-3}$ (severe), 0.36 $g \cdot m^{-3}$ (extreme) were considered for ice calculation. Under icing conditions, the distribution of the electric energy production along an optimal blade design was calculated, in order to locate the critical position on the blade that causes the highest power loss during icing events. The use of ice accretion and power loss models with different values of meteorological and geometric parameters enables the exploration to help locate the aerodynamic and mechanical effects along the blade. Several studies (Hochart et al., 2008; Lamraoui et al., 2013) have associated the value of liquid water content 0.2 $g \cdot m^{-3}$ to representative occurrences of atmospheric icing over Murdochville, and to the average of maximum values during winter months over Mont Belair (Canada). Therefore, a particular intention was given to production losses that are associated this typically assumed liquid water content.

Unlike helicopters that require power to rotate, wind turbines rotate to provide power. Due to the lack of studies that investigate the impact of freezing fraction on wind turbines production, the effect of freezing fraction on power requirements for helicopter is projected on wind turbine power production. To begin, this study identifies the critical location which corresponds to the most aerodynamically hazardous freezing fraction (Fortin and Perron, 2009) on the blade that holds the maximum power loss. Then, the corresponding temperatures for typical liquid water contents are determined, and finally power loss is evaluated (Fortin and Perron, 2009).

2.1. Generic wind turbine

The investigation was carried out on a generic horizontal axis wind turbine which is based on V80-1.8 MW Vestas characteristics. This type of wind turbine is commonly used in the province of Quebec (Canada). This wind turbine is characterized by a diameter of 80 m and a rated power of 1.8 MW that corresponds to a rated wind speed of 14 $m \cdot s^{-1}$. The minimum wind speed at which the wind turbine starts to be operational is 4 $m \cdot s^{-1}$. The blades have a variable pitch angle that corresponds to prevailing winds. The wind turbine rotates at approximately 16 rpm (Vestas).

2.2. Blade

The generic blades have a length of 40 m and are designed to provide more power and to minimize mechanical strains and sound. Since the blade design with more efficiency is complex and costly, a simplified alternative that represents a linear variation of the chord along the span was suggested (Burton et al., 2001).