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Numerical and field experimental investigation of wind turbine dynamic de-icing process

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ABSTRACT

A two-dimensional numerical approach has been proposed in this article to help with the simulation and visualization of dynamic de-icing process, thereby facilitating a better understanding of the pertinent physical phenomena involved in the ice melting process for cold-climate wind turbines. In this method, Reynolds-averaged Navier-Stokes equations and Shear Stress Transport k-ω turbulence model are adopted to calculate the outer fluid velocity field, and a two-step apparent heat capacity method has been employed to simulate the inner phase change. Corresponding field de-icing experiments on a 2 kW wind turbine have been performed at a natural icing station to provide essential parameters and subsequent validation for the simulation. The results show that the simulations are in good consistence with experiments. The relative errors between predicted actuation durations and measured ones are in acceptable range. Through comprehensive analysis of both numerical and experimental results, the wind turbine dynamic de-icing process has been explored. It is revealed that the de-icing process of wind turbine blades is mainly consisted of four distinct periods, i.e. sharp and short temperature-rising period, plateau period, gentle and long temperature-rising period, and fluctuation period (if exists). The mechanism of the generation of each stage has also been elucidated.

1. Introduction

Cold regions always spark a great interest for wind farms because that their higher air density will bring in an approximate 10% increment of wind power production (Fortin et al., 2005). Although cold-climate wind turbines have their advantages in power production, their blades are prone to suffer from problems caused by extreme environments. One of the major problems is ice accretion. Even small amount of ice that accreted on the leading edge will have a great impact on the aerodynamic performance of wind turbine blades. According to our observation on a 300 kW wind turbine, 30 min of glaze ice would bring in significant aerodynamic penalties and finally drive the wind turbine to a complete stoppage. Without the help of ice protection system, the wind turbine has to be shut down for the whole icing event. For frequent or extreme icing, wind turbines like this one may lose up to 30% of their annual production.

Many ice protection techniques for wind turbines, which are well summarized in (Dalili et al., 2009; Parent and Ilinca, 2011; Fakorede et al., 2016), have been proposed and developed to avoid serious aerodynamic losses or mechanical damages during icing events. Among all those techniques, most wind farm operators would prefer energy-free strategies like operational stops because they require almost no investment and extra retrofit of wind turbines. Taking the strategy of operational stops for example, it is believed that by stopping the wind turbine as soon as the icing event begins, the wind turbine can be restarted sooner after the icing event because of smaller ice accumulation. However, our operating experience of the 300 kW wind turbine is that although operators manually shut down the wind turbine in the incubation period of an icing event, the overnight ice accretion on the 14.6m blades are still quite considerable. As illustrated in Fig. 1, the amount, shape, and distribution of the overnight ice accretion, which look the same as the ice that deposited during operation, allow no early reboot of the wind turbine. This can be explained by the fact that even the wind turbine is shut down by adjusting the pitch angle to 90°, it will still rotate at a low speed of 2–4 rpm and gradually accumulate ice on the leading edge.

Hence, more effective ice mitigation strategies have to be adopted to remedy the disadvantages of energy-free strategies. Among all

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Fig. 1. 300 kW wind turbine and overnight ice accretion on its blade.

substitutions, the most reliable and promising one is the electro-thermal anti/de-icing technique which is taken from the aviation industry in the mid-1990s (Dalili et al., 2009). The biggest difference between aviation industry and wind energy industry is that the former concerns more about the maintenance of aerodynamic characteristics while the latter emphasizes more on energy consumption of the system. Therefore, wind turbine electro-thermal systems are normally preferred to operate in de-icing mode.

The key to designing, optimizing, and operating wind turbine electro-thermal de-icing systems is the understanding of dynamic de-icing process that takes place on the blades. Only by figuring out the de-icing process, it will be possible to find out the exact amount of heat flux to be provided and the actuation duration actually needed. However, most of the related researches are conducted on aircraft applications (Wright et al., 1991; Pourbagian and Habashi, 2015) with the assistance of professional icing codes like LEWICE, FENSAP-ICE (Reid et al., 2010, 2012), and ICECREMO2 (Harireche et al., 2008), which are validated to meet aeronautical industry specifications and are barely available to wind turbine researchers (Villalpando et al., 2016). As for wind turbines, the lack of basic experimental data, valid wind turbine blade dynamic de-icing model and powerful software tools makes it a quite complicated problem. Very limited progress either numerical or experimental has been reported in the open literature.

The purpose of this article is to provide a numerical approach to simulating the dynamic de-icing process for iced wind turbine blades. To that end, a transient model based on the apparent heat capacity method is employed to characterize the dynamic behaviors of ice melting. In order to validate this numerical approach and meanwhile provide experimental investigation for the de-icing process, field experiments are also performed. The combination of measured and calculated results enables primary investigation of the mechanisms of wind turbine dynamic de-icing process.

2. Numerical investigation

2.1. De-icing process analysis and assumptions

Upon the activation of wind turbine de-icing system, heat that generated by electricity will immediately warm up the ice-blade interface from its initial temperature. At the moment when the interface temperature reaches 0 °C, the energy will start altering the ice's molecular structure instead of creating a temperature rise and gradually turn the ice into water. During this phase change process, a subsequent volume compression is caused by the modification of material density. As for newly generated water which is called runback water, there is almost no chance for it to stand long on the surface due to high speed rotation of wind turbine. The runback water, as its name implies, will flow along the blade surface and then refreeze in unprotected regions. The gap caused by both volume compression and water loss will be immediately filled with air, contributing negatively to the conduction from heaters to the rest of ice. As the air gap gets wider and thicker, less and less energy will be able to break through the thermal barrier and can hardly support the ice-to-water phase change process as usual. Finally, a natural termination of this de-icing process will be reached when the air gap is big enough to connect to the external air.

In order to build up an efficient mathematical model for this dynamic de-icing process, the fluid velocity field, super-cooled water droplets impingement, and dynamic heat balance (including phase change process) ought to be calculated. Meanwhile, some assumptions are needed to be made so as to provide reasonable simplifications to the problem.

- The ice-to-water phase change is assumed to occur over a small temperature interval near the actual melting point to remove potential non-linearity for the model (Wright et al., 1991).
- Runback water is assumed to flow away soon after its appearance.
- The airfoil is assumed to be solid and made of fiberglass.

2.2. Fluid velocity field

It is well known that Navier-Stokes equations are usually adopted in describing motion of fluids around iced airfoil. However, due to restrictions of computing resources, direct solution to these famous equations for such a complex problem is hard to be found out. Therefore, it is a common practice to apply Reynolds-averaged treatment methods and meanwhile introduce well-established turbulence models like k-ε, k-ω, or k-ω SST turbulence model. The k-ω SST turbulence model (Menter, 1994), which is a combination of superior elements of k-ω and k-ε turbulence models, is adopted in this article to compute the fluid velocity field with acceptable calculation loads.

$$\rho\frac{\partial k}{\partial t} + \rho(\boldsymbol{u}\cdot\nabla)k = \nabla\cdot[(\mu + \mu_T\sigma_k)\nabla k] + P_k - \beta^{*}\rho\omega k \tag{1}$$