AN IMPROVED APPROACH FOR THE DETERMINATION OF IN-CLOUD ICING AT WIND TURBINE SITES

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ABSTRACT

Icing is an important issue when operating wind turbines in high altitudes or arctic areas as it can cause significant production losses and represent a safety risk.

In 2004, a 600 kW Enercon E-40 wind turbine with integrated blade heating was installed on Guetsch mountain, Switzerland, at 2'300 m asl. Coincidentally, a fully equipped test station of the Swiss meteorological network SwissMetNet is situated about 200 m from the wind turbine. The immediate proximity of the two facilities operating under icing conditions led to the launch of the national research project "Alpine Test Site Gütsch" which is embedded in the European "COST Action 727: measuring and forecasting atmospheric icing on structures".

When planning wind turbines in icing environment, it is crucial to know about the ratio between meteorological and instrumental icing, the latter being the cause of the first. The relation becomes especially important when the integration of a blade heating system for the wind turbine is considered. On Guetsch, a new approach to estimate the conditions for in-cloud icing was tested. The method, based on measurements of relative humidity, temperature and incoming long wave radiation, together with a correction of the relative humidity values at temperatures below 0°C led to a considerable improvement of the detection of in-cloud icing on Guetsch.

1. INTRODUCTION

Icing is an important issue when operating wind turbines in elevated or arctic areas as it can cause significant production losses and represent a safety risk [1]. In 2004, a 600 kW Enercon E-40 wind turbine with integrated blade heating was installed on Guetsch mountain, central Switzerland, at 2'300 m asl. Coincidentally, a fully equipped test station of the Swiss meteorological network SwissMetNet was installed about 200 m away from the wind turbine in 2003 (Fig. 1). The immediate proximity of the two facilities operating under icing conditions led to the launch of the research project "Alpine Test Site Gütsch: meteorological measurements and wind turbine performance analysis" [2, 3, 4] which is embedded in the European "COST Action 727: measuring and forecasting atmospheric icing on structures" [5, 6].

2. THE PROJECT

The project “Alpine Test Site Guetsch” is coordinated by the Federal Office of Climatology and Meteorology MeteoSwiss and the private met office Meteotest. The project partners come from Federal offices as well as industrial facilities. It is mainly sponsored by the State Secretariat for Education and Research SER and the Federal office of Energy SFOE. The project's main goals are:

- Inter-comparison of existing commercial and newly developed ice detection devices at the SwissMetNet test station Guetsch of MeteoSwiss.
- Performance monitoring of the nearby installed 600 kW Enercon E-40 wind turbine with integrated blade heating under icing conditions.

- Setting up tools and recommendations for estimating icing conditions at standard meteorological stations not equipped with ice detectors.
- Set up guidance in meteorological measurements and modelling to fulfil the needs of the industry (traffic, power transmission, wind energy) – especially for alpine conditions in Switzerland.

The project started in September 2005 and will last four years (2005-2009).

Figure 1: Alpine Test Site Guetsch. In the foreground, the meteorological test station can be seen, in the background the Enercon E-40 wind turbine.

3. SITE DESCRIPTION

The test site is located on a ridge in highly complex terrain in the midst of the Swiss Alps at 2'300 m asl (Fig. 2). The prevailing wind directions are north and south (Foehn). Winds are very variable and during strong Foehn events, wind speeds can easily reach 120 km/h or more. The long term average monthly air temperature varies from -6.9℃ in February to 7.3℃ in July and drops below 0℃ from November to April. The main icing periods are late autumn and early spring when the temperature often lies around 0℃. Icing can occur throughout the year. In mid winter the temperature can fall below -20℃.

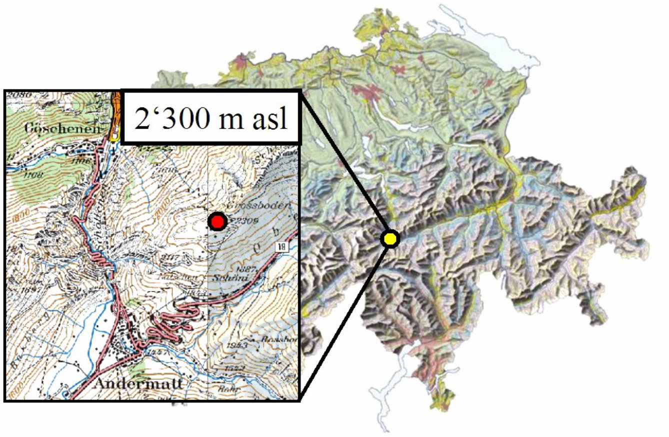

Figure 2: Location of the Alpine Test Site Guetsch.

4. METEOROLOGICAL AND INSTRUMENTAL ICING

In phase 1 of COST Action 727, a state of the art report about icing measurements was compiled by the members of the action [7, 8]. In this report the following definitions were introduced:

- Meteorological icing M_{icing}: duration of a meteorological event or perturbation which causes icing
- Instrumental icing I_{icing}: duration of the technical perturbation of the instrument due to icing
- Incubation time: delay between the beginning of the meteorological icing and the start of the instrumental icing
- Recovery time: delay between the end of the meteorological icing and the full recovery of the instrument

Figure 3 illustrates how wind measurements are affected by icing according to the definitions described above. From the point when icing conditions are given to the start of the meteorological icing, there is a certain delay until ice accretion at the anemometer begins, the incubation time. When ice accretion has started, the measured values cannot be used anymore for further analysis. Ice is accreted continuously to the sensor until the meteorological conditions for icing are not present anymore. But after the end of the meteorological icing, the ice will remain at the instrument for a certain time until it melts or falls off. This recovery time can be even longer than the period of meteorological icing. Although icing conditions are not given anymore, the readings of the instrument have to be discarded until the end of instrumental icing.

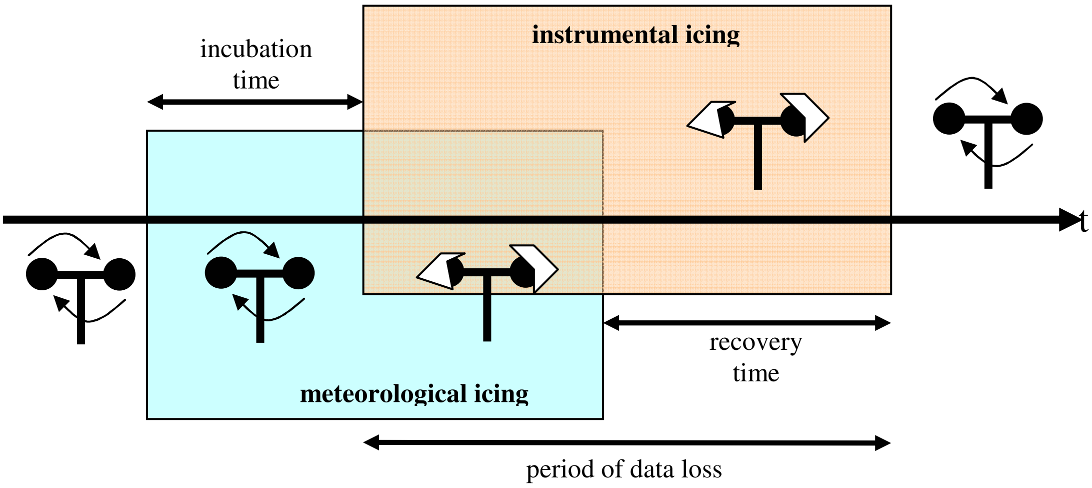

Figure 3: Illustration of the definitions of meteorological and instrumental icing.

For wind energy purposes, the ratio between meteorological and instrumental icing becomes especially important when the implementation of a blade heating is considered. If the periods of meteorological icing are short compared to the following instrumental icing, the use of a de-icing system will lead to a significant increase of power production compared to a wind turbine without such a system. On the other hand, if the periods of meteorological and instrumental icing are about of equal duration, there will be losses in production even with a de-icing system. In such cases an anti-icing system might be the only solution to optimize power production. Unfortunately, such systems are not available so far.

If the resource assessment is based only on wind measurements, it is impossible to distinguish between meteorological and instrumental icing. Therefore it cannot be estimated if a blade de-icing or anti-icing system would lead to an economic benefit for the operator or not.

5. THE METHOD

One project goal is to establish a simple method to estimate icing conditions on Guetsch without the use of ice detectors. This can be useful especially for the establishment of icing climatologies of a specific site e.g. for wind turbine planning. The icing rate is dependant on temperature, wind speed, liquid water content and particle size distribution of the air [9]. At present, there is unfortunately no automatic instrument capable of measuring the latter two parameters.
A widely used approach is the simple definition that icing occurs at air temperatures below 0℃ and a relative humidity higher that 95%. However, several studies showed that this approach is not able to reliably detect icing conditions [10, 11].
On Guetsch, icing mainly occurs as in-cloud icing. Therefore, a third parameter was introduced in order to estimate if the wind turbine is in-cloud or not by using the measured long wave incoming radiation L↓. This allows the calculation of the sky temperature T_{sky} according to Stefan-Boltzmann's law:

$$T_{sky} = \sqrt[4]{\frac{L\downarrow}{\sigma}} - 273.15 \qquad [°C]$$
$$\sigma = 5.67 \cdot 10^{-8} Wm^{-2}K^{-4}$$

When the cloud base is higher than the wind turbine (or if there are no clouds at all), the sky temperature is lower than the ambient air temperature. When the sky temperature gets close to or is equal to the air temperature at hub height, there is a high probability that the sensors, e.g. the nacelle of the wind turbine or the tip of the blades are in-cloud (fig. 4).

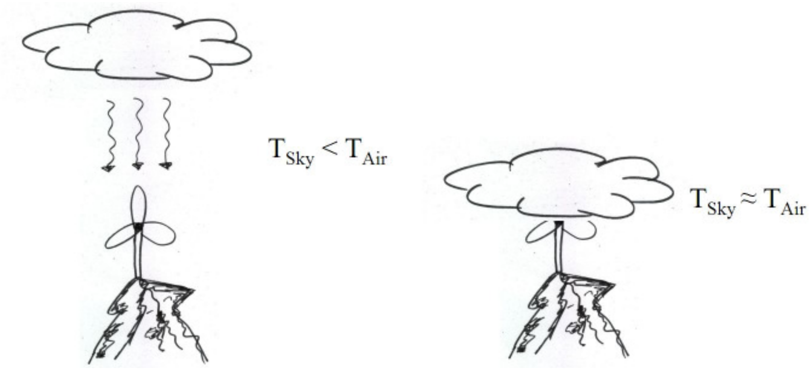

Fig. 4: Left: When the cloud base is higher than the wind turbine's nacelle, the sky temperature is significantly lower than the air temperature at the nacelle. Right: When the sky temperature is approximately equal to the air temperature, there is a high probability that the wind turbine's nacelle is in-cloud.

At the SwissMetNet station, measurements of temperature, relative humidity and incoming long wave radiation are available as standard values at 2 m agl. In order to compare the conditions at 2 m level with the situation at the wind turbine’s nacelle, the same measurements were performed at the hub height of 50 m with a Rotronic MP101A temperature and humidity sensor and a Kipp&Zonen CGR3 pyrgeometer. The measurement data was compared to webcam images which were taken of the rotor blades and the sonic anemometer mounted at the nacelle of the wind turbine [3]. These images were classified manually on the presence of icing and therefore represent an excellent database for the verification of the method.

6. RESULTS

During analysis of the relative humidity data, it became evident, that the measurements of relative humidity were performed according to WMO/CIMO standards where saturation water vapor pressure is always calculated with respect to water [12]. But below 0℃, saturation cannot be reached anymore using this procedure (fig. 5). In order to be able to use relative humidity as a parameter for the determination of icing conditions, the readings for relative humidity had to be re-calculated with respect to saturation water vapor pressure over ice for temperatures below 0℃. This led to an improvement of the detection of icing conditions of more than 10%.

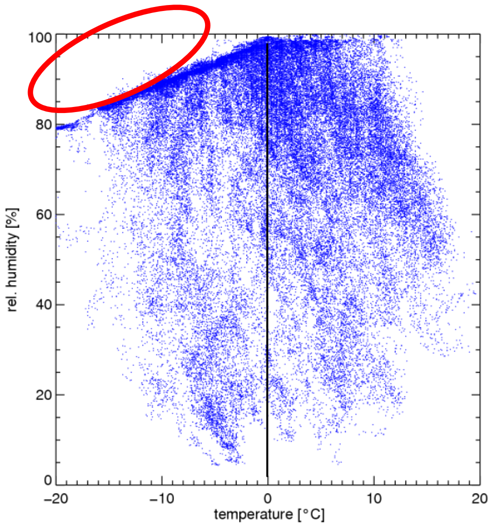

Figure 5: Relative humidity measured according WMO/CIMO standards does not reach saturation anymore at temperatures below 0℃ (red area).

When including the in-cloud detection, icing conditions were, in a first approach, defined as situations with air temperatures below 0℃, relative humidity above 95% and a difference between air temperature and sky temperature of less than 2℃. First analysis of the data is promising and seems to lead to an improvement of the detection of icing. A comparison between the met station (2 m agl) and the nacelle data (50 m agl) clearly shows that the wind turbine's nacelle is much more often in-cloud than the met station. A comparison of images from the met station and the wind turbine confirmed that on the nacelle of the wind turbine, icing happens more often and is of stronger nature than at the met station. This underlines the importance of carrying out icing measurements at the specific height of interest (e.g. at hub height for wind turbines).
The data analysis will be continued in order to be able to give a more precise statement about the suitability of this method to detect icing conditions.

7. CONCLUSIONS

The following conclusions could be drawn so far:

- Knowledge on the duration of meteorological and instrumental icing is an important parameter when planning wind turbines at locations with icing conditions in order to decide if de-icing or anti-icing systems are of economic interest or not.
- Based on wind measurements only, meteorological and instrumental icing can not be distinguished. In icing environments it is therefore crucial to include additional measurements such as temperature and relative humidity with the wind measurements.
- Standard devices measure relative humidity according to WMO/CIMO guidelines. Below 0℃ these values do not reach saturation anymore and are therefore not suitable for the detection of icing conditions. The values need to be re-calculated first.

- The determination of the incloudiness of the nacelle of the wind turbine based on measurements of incoming long wave radiation leads to an improvement of the detection of icing conditions.
- Icing occurs much more often at the nacelle of the wind turbine than at the met station near ground level. Therefore, the additional measurements of temperature, relative humidity and incoming long wave radiation should be carried out as close to hub height as possible in order not to underestimate the frequency of icing.

8. ACKNOWLEDGEMENTS

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