Four years of monitoring a wind turbine under icing conditions

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***Abstract*— Icing is an important issue when operating wind turbines in high altitude or arctic areas as it can cause significant production losses and represent a safety risk. The Swiss research project "Alpine Test Site Gütsch" which is embedded in the European "COST Action 727: measuring and forecasting atmospheric icing on structures", aims to extend the knowledge on icing on structures in the Swiss Alps.**

The ratio between meteorological and instrumental icing becomes important when the implementation of a blade heating is considered. Therefore, several additional measurement parameters were evaluated for their suitability to deliver this information. The study revealed, that in-cloud icing conditions can be detected fairly well by use of air temperature, relative humidity and the sky temperature, which is derived from incoming long wave radiation. It further showed that there is currently no ice detector on the market which is able to reliably measure icing. The monitoring of the Enercon E-40 wind turbine showed, that the ice detection via power curve seems to work considerably well except for light icing and during periods with low wind speed. However, this method gives no information if blades are still iced after heating cycle. This makes the automatic restart a safety risk. In many cases, not all the ice could be melted during one heating cycle, especially at the leading edge of the blades. The heat transfer to the leading edge therefore should be optimized. An extensive field study on ice throw revealed that ice throw is a safety risk especially during or right after a blade heating cycle and in the area under the blades

I. 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].

Fig. 1: Alpine Test Site Guetsch.

II. 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. 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°C in February to 7.3°C in July and drops below 0°C from November to April. The main icing periods are late autumn and early spring when the temperature often lies around 0°C. Icing can occur throughout the year. In mid winter the temperature can fall below -20°C.

Icing on Guetsch occurs mainly as in-cloud rime icing, mostly when winds from the North lift the humid air of passing fronts over the Guetsch ridge. Icing occurs regularly during winter time, but the ice loads are usually not very high (up to 6 kg/m). The duration of the ice accretion is in the range of hours, the persistence of the ice on unheated structures in the range of hours to single days.

III. Site Assessment under icing conditions

A. 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]. 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 2 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.

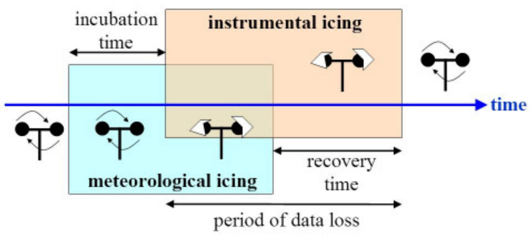

Fig. 2: Meteorological and Instrumental Icing.

B. Importance for wind energy

For wind energy purposes, the ratio between meteorological and instrumental icing becomes 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 such as a hot air blade heating or a 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 only anti-icing systems such as coatings might be the solution to optimize power production. Unfortunately, such systems are not available so far.

IV. Additional measurement parameters

A wind resource assessment is often based on wind measurements of an unheated anemometer. Within this data, only instrumental icing is visible when the sensor gets stuck. It is impossible to distinguish between meteorological and instrumental icing. Therefore it cannot be estimated if a blade deicing or anti-icing system would lead to an economic bene-fit for the operator or not. Several possible additional measurement parameters were evaluated for their suitability to deliver this additional information:

A. Heated vs. unheated anemometer

The comparison between a heated and an unheated anemometer can only give information concerning the duration of instrumental icing as the heated anemometer is (or should be) completely unaffected by icing. But the use of a heated anemometer certainly increases the accuracy of the evaluation of the wind potential itself as wind data is available throughout the whole time.

B. Temperature

Additional measurements of temperature give essential information about the occurrence of extremely low temperatures at the site. However, they cannot say anything about meteorological or instrumental icing as icing must not necessarily occur when temperature falls below 0°C (dry air).

C. Temperature and relative humidity

Measurements of temperature and relative humidity allow an indication about meteorological or instrumental icing. A widely used approach is the simple definition that icing occurs at air temperatures below 0°C and a relative humidity higher that 95%. However, several studies showed that this approach is not able to reliably detect icing conditions [8].

In addition, measurements of relative humidity are mostly performed according to WMO/CIMO standards where saturation water vapor pressure is always calculated with respect to water [9]. Below 0°C, saturation cannot be reached anymore using this procedure (fig. 3). In order to be able to use relative humidity as a parameter for the determination of icing conditions, the readings for relative humidity have to be recalculated with respect to saturation water vapor pressure over ice for temperatures below 0°C.

D. Temperature, relative humidity and incoming long wave radiation

When icing mostly occurs as incloud icing, the approach described above can be improved by use of the incoming long wave radiation L ↓ with a pyrgeometer. This allows the calculation of the sky temperature T_{sky} according to Stefan-Boltzmann's law:

$$T_{sky} = \sqrt[4]{\frac{L\downarrow}{\sigma}} - 273.15 \qquad [°C]$$

$$\sigma = 5.67 \cdot 10^{-8} Wm^{-2} K^{-4}$$

If 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. If 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. 3).

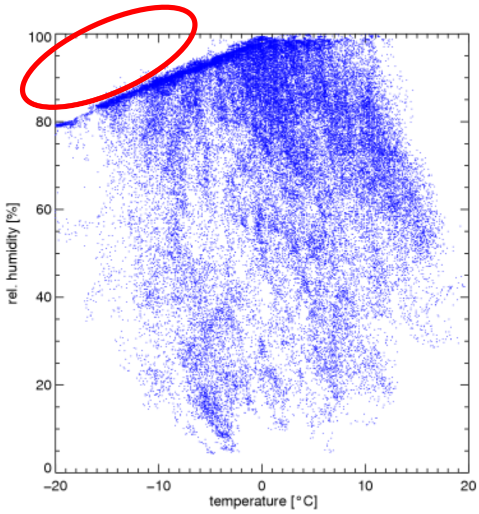

Fig. 3: Relative humidity measured according WMO/CIMO standards does not reach saturation anymore at temperatures below 0°C (red area).

In a first approach, icing conditions were defined as situations with air temperatures below 0°C, relative humidity above 95% and a difference between air temperature and sky temperature of less than 2°C. Data analysis showed promising results. A comparison between the met station and the wind turbine data clearly shows that the wind turbine's nacelle is more often in-cloud than the met station. A comparison of images from the met station and the wind turbine confirmed that icing happens more often and stronger at the nacelle of the wind turbine than at the met station [8]. This underlines the importance of carrying out icing measurements at the specific height of interest (e.g. at hub height for wind turbines).

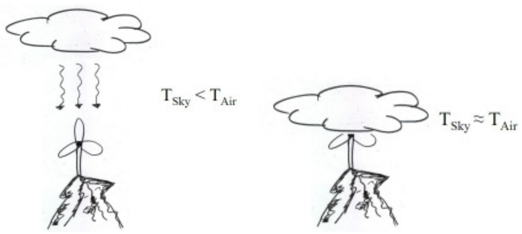

Fig. 3: Left: when the cloud base is higher than the wind turbine's nacelle, the sky temperature is significantly lower than the air temperature at the nacelle. Right: when the sky temperature is approximately equal to the air temperature, there is a high probability that the wind turbine's nacelle is in-cloud.

E. Temperature, relative humidity, incoming long wave radiation and wind speed (heated anemometer)

Icing is dependent on wind speed as wind is transporting the water droplets in the air and forces them to collide with a structure. Currently, first studies are carried to verify if the inclusion of wind speed leads to an improvement of the detection of icing conditions.

F. Ice Detectors

The most reliable instrument to detect icing conditions is the ice detector. Unfortunately, a comprehensive intercomparison of commercially available ice detectors on the Guetsch site clearly showed that there is currently no instrument available which reliably and automatically measures ice accretion [10, 11]. However, two promising instruments could be identified (Fig. 4):

- The Combitech Mk I IceMonitor is manufactured according to ISO 12494. It uses a freely rotating vertical cylinder and measures the weight of ice accreted on the probe.
- The Goodrich ice detector 0872J1 has a probe that oscillates at 40 kHz and monitors the frequency change due to ice accretion. A heater melts the ice at regular intervals depending on the accretion rate.

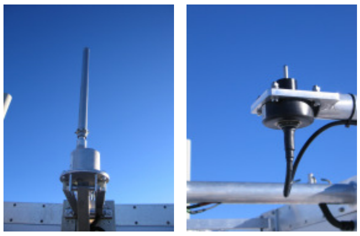

Fig. 4: Left: Combitech IceMonitor, right: Goodrich Ice Detector.

V. Performance of Wind Turbine under Icing Conditions

The performance of the wind turbine on Guetsch with respect to power production, ice detection and efficiency of the blade heating was monitored by use of the operational data as well as the installation of web cams monitoring the nacelle anemometer and the rotor blades [12].

A. Monitoring of the wind turbine's blade heating

The wind turbine's blade heating is basically controlled by comparison of the turbine's effective power production and the theoretic power production, which is computed from measured wind speed and the turbine's power curve. If icing is detected, the power production is stopped and each blade is heated with a 4 kW hot air fan for 90 minutes. Afterwards, power production is resumed.

In general, the performance analysis of the ice detection showed good results. However, after comparison with the webcam images, it turned out that icing on blades cannot be detected with this method when wind speed is low. Furthermore, this procedure is not suitable for detecting light icing. Therefore, icing might occur at low wind speeds but is only detected when wind speed increases and the turbine resumes power production. Thus, the heating process takes place during a period with high wind speed which makes the loss in power production is higher than if the blade would have been de-iced before. Finally, this approach is not capable to determine if, after a blade heating cycle, the blade is icefree or not. This makes the automatic restart of the turbine a safety risk.

B. Monitoring of the blade heating

In many cases the accreted ice could not be fully removed from the blades, especially from the leading edge, during one heating cycle but only after several additional heating cycles. This resulted in a higher loss in power production and allows the possibility that the wind turbine resumes operation while there is still some ice on the blades: this significantly increases the risk of ice throw. It seems that the heat transfer to the leading edge of the blades should be optimized.

VI. Ice throw

As the wind turbine is located close to ski slopes, ice throw is an important safety issue [13]. In order to achieve more information about the ice throw of the wind turbine, the area around the wind turbine was, if accessible, inspected after every icing event by a local person for ice fragments that had fallen off the blades. Distance from and direction relative to the turbine as well as size and weight of the recovered fragments were mapped and, together with photos, collected in a data base.

Until now, more than 250 fragments could be recorded, some of them even during summer time. The maximum distance was 92 m, the maximum weight 1.8 kg. The theoretical maximum distance according to [13] of 135 m was not reached so far. Figure 5 shows the distribution of the ice fragments around the wind turbine, figure 6 an example of ice throw which occurred in the middle of the summer.

Approximately 40% of the fragments were found within a distance of 20 m from the wind turbine (rotor diameter 40 m). This makes the area under the blades the most dangerous area concerning ice throw. The studies revealed that Ice throw is a significant safety risk at the Gütsch site. Therefore warning signs have been installed and a nearby winter walking trail was placed further away from the wind turbine [14].

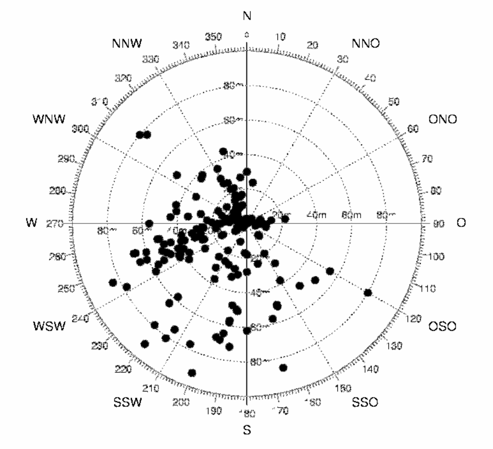

Fig. 5: Distribution of ice throw around the turbine.

Figure 3: Photo of ice fragments

VII. Conclusions

Concerning the topics discussed in this paper, the following conclusions can be drawn:

- Additional parameters need to be measured for a reliable distinction between meteorological and instrumental icing for a reliable site assessment under icing conditions
- In cloud icing conditions can be detected fairly well by use of air temperature, relative humidity and the sky temperature which is derived from incoming long wave radiation
- Currently, there is no instrument available on the market which is capable of measuring icing reliably. However, the Combitech IceMonitor and the Goodrich Ice detector seem to be promising instruments
- The ice detection of the Enercon E-40 via power curve seems to work considerably well except for light icing and during periods with low wind speed
- This ice detection method gives no information if blades are still iced after heating cycle. This makes the automatic restart a safety risk.
- Often, not all the ice can be melted during one heating cycle, especially at the leading edge of the blades. The heat transfer to the leading edge therefore should be optimized
- Ice throw is a safety risk especially during or right after a blade heating cycle and in the area under the blades

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