Alpine Test Site Guetsch
Meteorological measurements and wind turbine performance analysis

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***Abstract*—The goal of the Swiss project "Alpine Test Site Gütsch" is to expand the knowledge base on atmospheric icing specifically in the Alps. The project includes an inter-comparison of ice detectors, the performance monitoring of a wind turbine and recommendations for the estimation of icing conditions at sites not equipped with ice detectors. The ice detector inter-comparison showed surprisingly poor results so far, no device being able to measure icing correctly for a whole winter season. The monitoring of the wind turbine pointed out deficiencies concerning ice detection as well as blade heating performance. An extensive observation of the wind turbine's ice throw proved that a significant safety risk has to be taken into account at this site. Furthermore, a simple meteorological approach to identify icing conditions was tested with fairly good results and finally, modeling of two icing events with the NWP model WRF was accomplished, showing promising agreement with on site observations.**

Fig. 1: Alpine Test Site Guetsch. In the foreground: the SwissMetNet station, in the background: the Enercon E-40 wind turbine.

I. Introduction

THERE is worldwide an increasing demand for accurate information on icing in cold climate and mountainous regions, mainly to fulfill the growing needs of meteorological information for various human activities, such as construction, recreation and utilization of natural resources, in particular of wind energy.

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 a.s.l. Coincidentally, a fully equipped test station of the Swiss meteorological network SwissMetNet was installed about 150 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 Guetsch: meteorological measurements and wind turbine performance analysis [1]" which is embedded in the European "COST Action 727: measuring and forecasting atmospheric icing on structures [2, 3]". The project's goal is to expand the knowledge base on atmospheric icing specifically in the Alps.

II. Project Description

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 Gütsch 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 three years (2005-2008).

III. 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 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 frequently lies around 0°C. Icing can occur throughout the year. In mid winter the temperature may fall below -20°C.

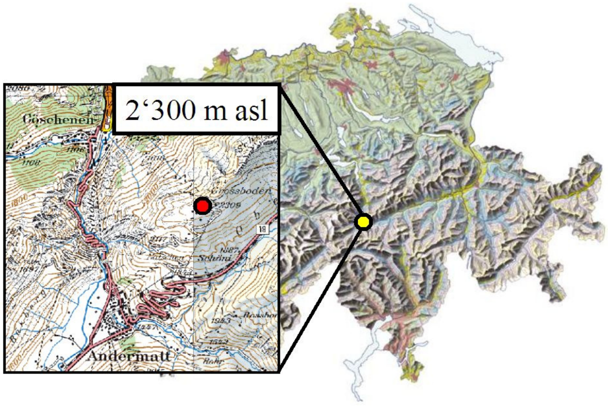

Fig. 2: Location of the Alpine Test Site Gütsch in Switzerland.

IV. Ice Detector Inter-comparison

The Guetsch test station has been expanded with numerous measurements systems during summer 2006. On one side, the station is fully equipped with standard instruments as defined for the SwissMetNet network. On the other side, a number of new meteorological instruments have been implemented in order to test their robustness to harsh environment for other meteorological applications. All sensors were monitored regularly by an automatic camera.

Concerning the instruments dedicated to icing measurements, unexpected difficulties have dramatically slowed the installation of these instruments:

- The operating software of the SwissMetNet has unfortunately endured some stability problems which prevented a full scale installation during the summer 2006.
- Many of the instruments have been delivered with special, non standard output formats which have been often difficult to integrate in the operating software.
- The instrument themselves have proved to be more difficult than expected to adapt for harsh conditions.

The results of the ice detector inter-comparison performed at the Guetsch station are rather disillusioning and can be summarized as follows:

A. *Combitech IceMonitor*

This instrument represents the nearest adaptation to the ISO-12494 definition [4], measuring the ice load on a freely rotating vertical rod as shown in figure 3. However, the black protection cap at the bottom of the sensor was lifted up the rod and blown away during a moderate Foehn event (fig. 3 right side). As a consequence, the bearing got frozen under icing conditions, preventing the sensor from rotating. The same effect was observed at the Luosto test station in Finland. In order to prevent such behavior, the protection cap was fixed with a clamp on the rod. Unfortunately, the sensor became very sensitive to tilted wind flow as the rod was lifted when wind came from below. This resulted in load differences of up to 300 g without presence of any ice which made the interpretation of the data very difficult.

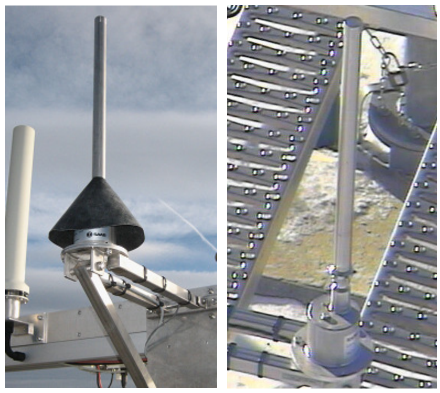

Fig. 3: Left: Combitech IceMonitor installed on the Guetsch test site. Right: Combitech IceMonitor after loss of the black protection cap.

B. *Czech IceMeter*

This instrument weights the ice load on a vertical non rotating rod. Unfortunately it has never worked properly on the Guetsch site. Similar experiences were made at the Luosto test station in Finland as well at the Sternwald site in Austria [5].

C. *HoloOptics T20*

This sensor detects ice by reflection of infrared light. First laboratory tests showed very promising results. Unfortunately, poor manufacturing and water leaks in the structure resulted in consequent damages of the internal electronic and instrument failure. Two revised versions have been installed during winter 2006/07 without success.

D. *Infralytic*

This instrument is based on reflection of infrared light on an ice film. The light beam is sent through a fiber optic cable and reflected on the ice surface. The sensor can thus also be installed on the leading edge of a wind turbine’s blade. For usage in an automatic meteorological station, some modifications had to be undertaken. A prototype has delivered excellent laboratory results and will be installed on the Guetsch site as soon as possible.

E. Rosemount/Goodrich 0847LH1

This ice sensor detects ice by frequency changes on a vibrating finger (fig. 4) and has shown promising results in earlier tests [5, 6]. Unfortunately the instrument was delivered without female connector to plug the data cable to the sensor. It proved impossible to get such spare part from the manufacturer in the USA due to military regulations. However, internal solutions could be found and the instrument was finally installed on the Guetsch site at the very end of winter 2006/07. Therefore, hardly any icing data could be collected with this sensor so far.

Fig. 4: Rosemount/Goodrich Ice detector.

F. Vibrometer

This instrument is based on the same measurement principle as it does the Rosemount/Goodrich sensor. This sensor is the only prototype manufactured already a long time ago by the Swiss company Vibrometer. Therefore only poor documentation and no support are presently available. This makes it very difficult to interpret the measured data.

For the projects last winter period 2007/08, the main focus will be put on the two most promising and most developed ice detectors, the Combitech IceMonitor and the Rosemount/Goodrich ice detector. This procedure is in line with the COST Action 727 which selected the same instruments as reference instruments.

V. Monitoring of the Wind Turbine

Icing is an important issue when operating wind turbines in elevated or arctic areas because of significant production losses and safety risks [7, 8]. Therefore, the Guetsch wind turbine was extensively monitored in order to get information about its performance under icing conditions.

A. Collection of operating data

The operating data of the wind turbine such as wind speed at hub height, power production, air temperatures at ground, hub height and inside the blades as well as the state of the blade heating were recorded as 10-minute-averages, synchronized with the measurements of the meteorological station and stored into a dedicated data base which allows for the analysis and correlation of the meteorological conditions and the wind turbine performances during icing events.

B. Visual observation

The availability of continuous live images of the wind turbine's blades is crucial for a performance analysis under icing conditions. During former projects, cameras were installed inside or outside the hub pointing towards the blade [9].

On Guetsch, another approach was developed: a commercially available Mobotix web cam was installed on the nacelle of the wind turbine (fig. 5) and the passing blade is signaled by the use of video motion detection [10]. An image of the blade is recorded every 30 minutes and automatically sent to the project's ftp server. For the interested readers, the regularly updated images can be seen on the project's website [1]. All images are filtered manually on ice accretion.

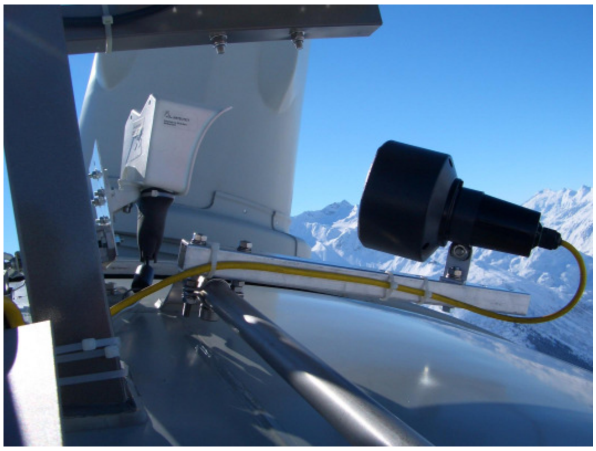

Fig. 5: Web cam mounted on the nacelle of the wind turbine.

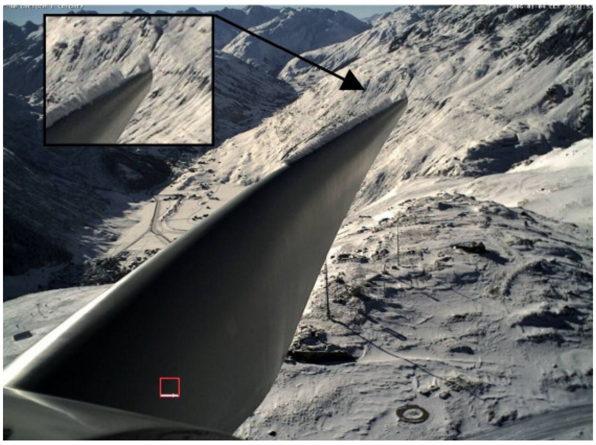

Fig. 6: Image taken by the web cam at the wind turbine's nacelle showing the wind turbine's blade with rime icing. The red box marks the sensitive area for the video motion detection

In addition, a second webcam pointing to the wind turbine's nacelle sonic anemometer was installed. Again, images are taken every 30 minutes, automatically put to the project's website and filtered manually.

The analysis of the camera images showed, that icing on Guetsch mostly occurs during nighttime. Unfortunately the camera system, as installed on the wind turbine, is not adapted to taking pictures of the wind turbine's blades during the night. However, a new system with a new, more sensitive camera and infrared headlights is going to be implemented for the last project winter. Furthermore, the comparison of the blade and the anemometer images showed that icing takes place earlier on the blades than on the sonic anemometer. This seems logical as wind speed at the tip of the moving blade is significantly higher than at the fixedly sonic anemometer.

C. *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 has started resuming power production. Thus, the heating process takes place during a period with high wind speed so that the loss in power production is higher than if the blade would have been deiced before.

In addition, in many cases the accreted ice could not be removed from the blades during one heating cycle but only after several additional heating cycles. This also resulted in a higher loss in power production and led to 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.

D. *Ice throw*

As the wind turbine is located almost within a ski resort, ice throw is an important safety issue [11]. Consequently, the area around the wind turbine was inspected after every icing event 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 (fig. 7), collected in a data base.

Up to now, more than 140 ice fragments with weights of up to 1'800 g could be recorded in distances of up to 92 m from the wind turbine (fig. 8). Most likely, ice throw happened during or right after a blade heating cycle. Either the ice slides along the blades towards the ground when the turbine is at standstill or the ice is thrown off the blades when the wind turbine resumes power production. Therefore, the area around the tower and under the blades is the most dangerous place concerning ice throw. About 40% of the ice fragments were found within a distance of 20 m to the wind turbine [12].

Fig. 7: Ice Throw from the wind turbine on Guetsch found in August 2006.

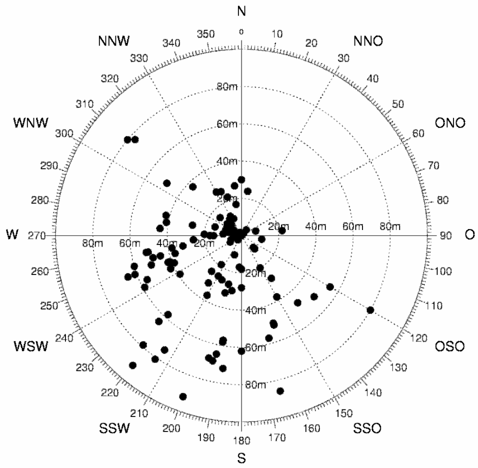

Fig. 8: Distribution of ice throw around the wind turbine on Guetsch.

The theoretical maximum throwing distance of d = 135 m given by [11]

$$d = (D + H) \cdot 1.5$$

D = rotor diameter [Guetsch: 40 m]
H = hub height [Guetsch: 50m]

was not reached during this study so far.

The study made clear, that ice throw occurs regularly and at any time of the year at the Guetsch site. Therefore warning signs were installed and a nearby winter walking trail was placed further away from the wind turbine.

VI. Meteorological detection of Icing Conditions

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 LWC and particle size distribution of the air [13]. 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°C and a relative humidity higher that 95%. However, several studies showed that this approach is not able to reliably detect icing conditions [6].

On Gütsch, 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:

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

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

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. 9 and 10).

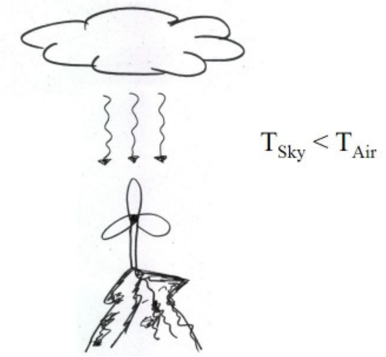

Fig. 9: When the cloud base is higher than the wind turbine's nacelle, the sky temperature is significantly lower than the air temperature at the nacelle.

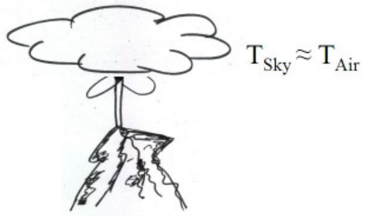

Fig. 10: When the sky temperature is approximately equal to the air temperature, there is a high probability that the wind turbine's nacelle is in-cloud.

At the SwissMetNet station, measurements of temperature, relative humidity and incoming long wave radiation are available as standard values. 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 hub height [10]. Measurement of relative humidity was in both cases performed according to WMO/CIMO standards where saturation water vapor pressure is always calculated with respect to water [14]. Below 0°C, saturation cannot be reached anymore using this procedure. 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°C.

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. First analysis of the data is promising and seems to lead to an improvement of the detection of icing conditions. 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 on the nacelle of the wind turbine than at the met station [6]. This underlines the importance of carrying out icing measurements at the specific height of interest (e.g. at hub height for wind turbines).

VII. Icing Modeling with the WRF Model

During a short term scientific mission supported by the COST Action 727, two icing events on Guetsch were modeled by the Norwegian meteorological institute with the non-hydrostatic mesoscale numerical weather prediction model WRF [15] by applying the Thompson scheme for cloud microphysics [16]. Modeled temperature, wind speed and cloud water were inserted into the icing model described in [13] in order to obtain the icing rate.

The results showed a good agreement on time and duration of the icing periods whereas ice loads were rather underestimated. Further analysis of the results showed, that the very complex topography of the Gütsch site was not fully represented by the digital terrain model DTM used for the modeling. Furthermore, the special alpine situation puts high requirements on computing time and setting of boundary conditions. Simulations at topographically less demanding sites such as Deadwater Fell in the UK or at Mt. Ylläs in Finland [17] yielded impressive results.

In a further step, the WRF model will initialized with the newest 2.2 km forecast Model COSMO-2 operated by MeteoSwiss [18] in order to achieve a higher resolution of the DTM.

VIII. Conclusions

After two of three project winters of the "Alpine Test Site Guetsch" project, the following main conclusions can be drawn:

- Currently, there is no instrument available on the market which is capable of measuring icing reliably.
- The Enercon E-40 wind turbine shows a considerably good performance under icing conditions with small deficiencies of ice detection as well as of blade heating performance.
- Ice throw represents a significant safety risk on Guetsch throughout the whole year. The most dangerous area is under the blades. The most dangerous time is during or right after a blade heating cycle.

- 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.
- Icing modeling with NWP models such as the WRF model delivers promising results and might become a valuable alternative to on site icing measurements.

IX. Acknowledgments

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