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Bern, February 16, 2016

Evaluation of ice detection systems for wind turbines

Final report

VGB Research Project No. 392

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Disclaimer

All information presented in this report is solely based on documents provided by the manufacturers of the ice detection systems as well as publicly available reports, papers and presentations. No data analysis has been carried out by Meteotest for this report. Especially the information on the accuracy of the systems has not been checked or validated by Meteotest or by TÜV NORD.

Acknowledgements

The research project "Evaluation of ice detection systems for wind turbines" was funded by VGB PowerTech e.V., which is kindly acknowledged. The project was initiated and supervised by the VGB Technical Committee "Wind Energy." The authors would like to thank the companies EnBW, Enercity (Stadtwerke Hannover), Energiewerkstatt, ESB Renewables, EVN Naturkraft, Fortech, GDF Suez Canada (now Engie) , GDF Suez Europe (now Engie), RheinEnergie, Vattenfall and WSB Service Deutschland for their active participation in the survey among wind-turbine operators conducted within the project. Finally the authors wish to thank all manufacturers of ice detection systems for their active and transparent collaboration in the project.

Version	Date	Document	Project Number
1	16.02.2016	Final Report	15_025

Editing	Name	Date
Created by	René Cattin, Dr. Ulla Heikkilä	22.12.2015
Controlled by	Dr. Ulla Heikkilä	23.12.2015
Approved by	Dr. Saskia Bourgeois	30.12.2015
Reviewed by	Oliver Raupach, Felix Storck TÜV NORD SysTec GmbH & Co.KG	29.01.2016
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Summary

Atmospheric icing has a significant impact on the development and the operation of wind parks. To reach an optimal performance, the turbine must first be able to detect ice on the rotor blades immediately when it occurs. Second, it must provide a signal which states that the rotor blade is free of ice and thus normal operation can be resumed.

The goal of this report is to provide an independent overview on ice detection systems commercially available. The report consists of basics and important definitions regarding icing on structures. The main part is a detailed description of the ice detection systems based on information provided by the system manufacturers as well as publicly available documentation. Afterwards, the different systems are compared in an evaluation matrix. Additionally, short overviews on ice protection systems for wind turbines and on the state of the art regarding icing forecasts are given.

There are two different types of ice detection systems being evaluated and compared in the report:

- **Nacelle based systems:** ice detection with instruments installed at one point on the nacelle of a wind turbine.

- **Rotor blade based systems:** ice detection with devices installed on the rotor blade.

All nacelle based systems measure instrumental icing and therefore do not represent the effective conditions on the rotor blade. For a safe and efficient operation of wind turbines under icing conditions, measuring rotor icing is mandatory.

10 nacelle based systems and methods have been evaluated. The Labkotec LID-3300IP and the Goodrich 0871LH1 model have the highest technical maturity and the highest number of systems in use. Furthermore, they are the only certified systems. Several independent field studies exist for most systems. These studies show that all systems have their shortcomings under specific conditions.

5 blade based systems and methods have been evaluated. The power curve method is applied very frequently. The Bosch Rexroth BladeControl system has the highest number of systems in use. The other systems have significantly smaller numbers of systems in use. This is explained by the fact, that the fos4IceDetection, Wölfel IDD.Blade and eologix are very new systems. All blade based systems are certified. No independent field studies exist for the blade based systems.

The power curve method is the only blade based system which is not able to detect rotor icing during stand still of the wind turbine. All systems except the eologix system require a minimum wind speed of 2 m/s or higher to be able to detect rotor icing. The eologix system is the only system one which does not require access to real-time operational data of the wind turbine (pitch angle, rotational speed, wind

speed). At the same time, eologix is the only blade based system which measures icing at specific spots on the rotor blade. The other systems are able to detect ice anywhere on the blade with increasing sensitivity towards the blade tip. The power curve method as well as the fos4IceDetection and the eologix system do not require any electrical wires in the blade. All blade based systems can be retrofitted.

Contents

1 Introduction

Atmospheric icing has a significant impact on the development and the operation of wind parks. The ice disturbs the aerodynamics of the rotor blades and thus causes production losses and increased noise emissions. Moreover, the additional ice loads may lead to extreme loads and increased fatigue. Iced wind measurement sensors at the wind turbine's nacelle may lead to erroneous behavior and security stops. During project development, wind measurements are disturbed by icing resulting in a higher uncertainty of the calculations of annual energy production AEP and a higher cost of investment. Finally, ice throw and ice fall from the iced wind turbine rotor blades represent a significant safety risk for passersby and service personnel.

Wind energy under icing conditions was a niche market for a long time as wind energy was much easier to harvest in coastal regions with moderate climates. Furthermore, offshore sites seemed easier to exploit than regions with cold climate, resulting in much stronger research and development efforts for offshore wind energy. Today, the situation has changed: Offshore wind energy development is facing unforeseen technical problems and higher costs than expected. Less coastal regions are available for development. Therefore, developers and investors are beginning to shift their focus on new sites with attractive wind conditions in areas affected by icing in northern Scandinavia, North America and mountainous regions all over Europe. A market study by BTM Navigant[1] predicts further strong growth of the cold climate sector in the next years.

However, development and operation of wind parks under icing conditions still has a pioneering character. Standards and guidelines as well as technical solutions for planning and operation of wind parks under icing conditions are – although they exist – still under development. Furthermore, sinking electricity prices increase the pressure on existing projects to maximize the production in order to stay profitable.

In this context, an optimized and efficient operation of wind parks under icing conditions has become a very important issue for wind farm operators. On the one hand, it is in the operators' interest to keep the production losses due to icing as low as possible. On the other hand, the safety of passersby and service personnel has to be guaranteed at all times and extreme loads have to be avoided.

To reach an optimal performance, the turbine must first be able to detect ice on the rotor blades immediately when it occurs in order to either stop the turbine or to activate a de-icing system. Second, a signal has to be supplied which states that the rotor blade is free of ice and thus normal operation can be resumed. In this context, ice detection systems play a central role.

The goal of this report is to provide an independent overview on ice detection instruments commercially available. The study is meant to provide basic information

1 Navigant Research, BTM World Market Update 2012

for operators of wind farms under icing conditions to review and optimize the operation of their wind farms.

The first part of the report consists of basics and important definitions regarding icing on structures. The main part is a detailed description of the ice detection systems based on documentation provided by the manufacturers as well as publicly available reports, papers and presentations. Finally, the different systems are compared in an evaluation matrix. Additionally, short overviews on ice protection systems for wind turbines and on the state of the art regarding icing forecasts are given in this report.

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2 Icing basics and important definitions

2.1 Cold climate

Cold climate (CC) areas are regions where atmospheric icing or periods with temperatures below the operational limits of standard wind turbines occur (typically -10°C for operation, -20°C for survival). Cold Climate may impact project implementation, economics and safety. Areas where periods with temperatures below the operational limits of standard wind turbines occur are defined as Low Temperature Climate (LTC) whereas areas with atmospheric icing are defined as Icing Climate (IC). In some areas wind turbines are only exposed to either atmospheric icing or low temperatures. In some regions both low temperatures and atmospheric icing may take place. Therefore, a site can be in a Low Temperature Climate or in an Icing Climate or both while they are still all denoted Cold Climate sites. These definitions are illustrated in Figure 1.

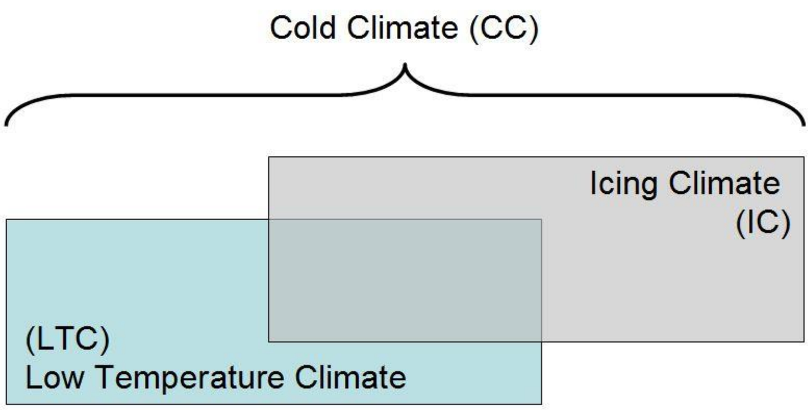

Figure 1: Definition of Cold Climate, Low Temperature Climate and Icing Climate.[2]

2.2 Atmospheric icing

Atmospheric icing is defined as the accretion of ice or snow on structures, which are exposed to the atmosphere. In general, two different types of atmospheric icing that impact wind turbine development can be distinguished: in-cloud icing (rime ice or glaze) and precipitation icing (freezing rain or drizzle, wet snow).

The different forms of atmospheric icing can be described as follows:

- **Rime ice**: Supercooled liquid water droplets from clouds or fog are transported by the wind. When they hit a surface, they freeze immediately. If the

[2] IEA Wind Task 19, 2012, Recommended Practices for Wind Energy Projects in Cold Climates, edition 2012

droplets are rather small, soft rime is formed, if the droplets are bigger, hard rime is formed. Its formation is asymmetrical (often needles) on the windward side of a structure. It can occur at temperatures down to -20°C.

- **Glaze ice**: Glaze ice is caused by freezing rain, freezing drizzle or wet in-cloud icing and forms a smooth, transparent and homogenous ice layer with a strong adhesion on the structure. It usually occurs at temperatures between 0 and -6°C. Glaze is the type of ice having the highest density. Freezing rain or freezing drizzle occurs when warm air melts the snow crystals and forms rain droplets, which afterwards fall through a freezing air layer near the ground. Wet in-cloud icing occurs when the surface temperature is near 0°C. Here, the water droplets which hit the surface do not freeze completely. A layer of liquid water forms which, due to wind and gravity, may flow around the object and freeze also on the leeward side.

- **Wet snow**: Partly melted snow crystals with high liquid water content become sticky and are able to adhere on the surface of an object. Wet snow accretion therefore occurs when the air temperature is between 0 and +3°C.

2.3 Phases of an icing event

As shown in Figure 2, an icing event can be described with the following expressions, applicable to all structures, and instruments and wind turbines exposed to atmospheric icing[3]:

- **Meteorological Icing:** Period during which the meteorological conditions allow ice accretion.

- **Instrumental Icing:** Period, during which the ice remains at a structure and/or an instrument.

- **Rotor Icing:** Period, during which ice is present at the rotor blade of a wind turbine. Due to different dimension, shape, flow velocity and vibrations of the rotor blades compared to nacelle based instruments, rotor icing is not equivalent to instrumental icing. Typically, incubation and ablation time for rotor icing are shorter than for instrumental icing. The duration of rotor icing strongly differs for a wind turbine at stand still compared to a wind turbine which is allowed to operate under icing conditions.

- **Incubation**: Time between the start of meteorological icing and the start of instrumental/rotor icing, depending on the surface and the temperature of the structure.

- **Accretion**: Period of ice growth (active ice formation).

[3] IEA Wind Task 19, 2016, Recommended Practices for Wind Energy Projects in Cold Climate, edition 2016, publication expected mid 2016.

- **Persistence**: Period, during which the ice remains persistent (no growth, no ablation).
- **Ablation:** Period, during which the ice is being removed through ablation. Ablation includes melting, erosion and sublimation of the ice. It can also be defined as the time between the end of meteorological icing and the end of instrumental icing.

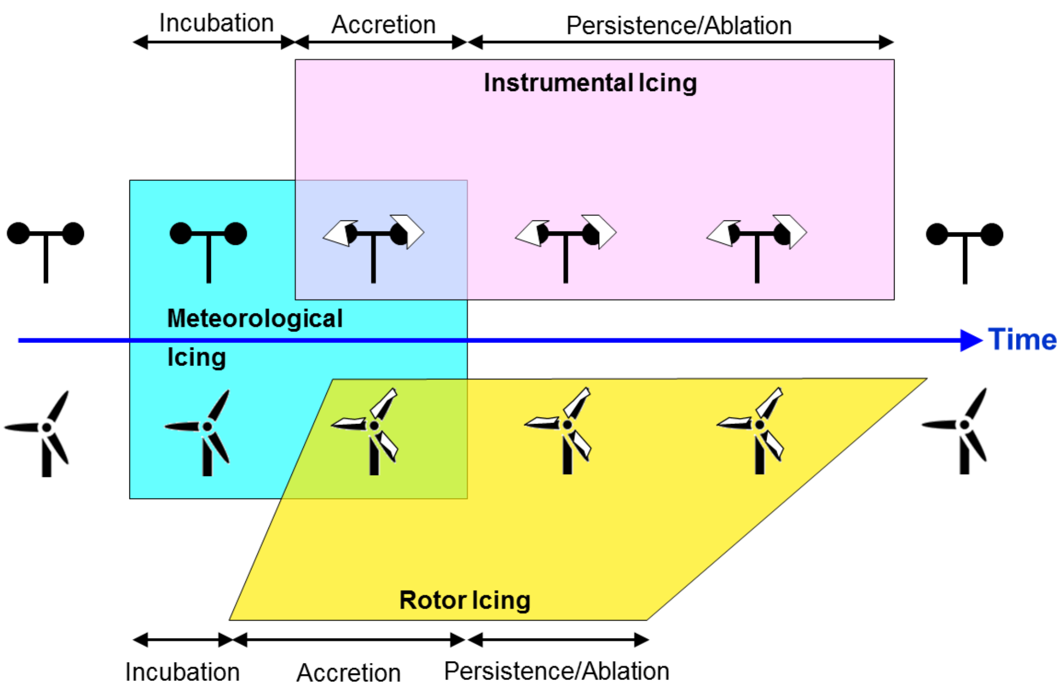

Figure 2: Illustration of meteorological icing, instrumental icing, rotor icing, incubation, accretion, persistence and ablation. The duration of rotor icing strongly differs for a wind turbine at stand still compared to a wind turbine which is allowed to operate under icing conditions.

2.4 IEA site classification

The Wind R&D Task 19 "Wind Energy in Cold Climates" of the International Energy Agency (IEA) has defined five different classes for icing to describe the severity of icing for wind energy sites[4]. These classes depend on the length of meteorological and instrumental icing events and production loss at a specific site (Table 1).

[4] 2012: IEA Wind Recommended Practices: Wind Energy in Cold Climates

Table 1: Definitions of IEA Ice classes.

IEA ice class	**Meteorological icing**	**Instrumental icing**	**Production loss due to icing**
	% of year	% of year	% of annual production
5 (strong)	> 10	> 20	> 20
4 (moderate to strong)	5 - 10	10 - 30	10 - 25
3 (moderate)	3 - 5	6 - 15	3 - 12
2 (light to moderate)	0.5 - 3	1 - 9	0.5 - 5
1 (light)	0 - 0.5	0 - 1.5	0 - 0.5

2.5 Ice Detection

Ice detection systems for operation of wind turbines have to provide two different signals:

- **Detection of "ice"** refers to the **start of rotor icing** of a wind turbine in order to activate a de-icing system, if applicable, or bring operation to a stop for safety reasons.
- **Detection of "no ice"** refers to the **end of rotor icing**, when the rotor blade has become ice-free again. The detection of "no ice" is equally important to resume operation as soon as possible.

In order to minimise production losses these detection methods should be efficient and reliable. A schematic view of the performance of an ice detection system is given in Figure 3.

There are two different types of ice detection systems:

- **Nacelle based systems:** ice detection with instruments installed at one point on the nacelle of a wind turbine.
- **Rotor blade based systems:** ice detection with devices installed on the rotor blade.

All nacelle based systems measure instrumental icing and therefore do not represent the effective conditions on the rotor blade. Therefore, their readings have a considerable uncertainty with respect to turbine operation. First, the tip of a rotor blade spans a much larger altitude range than the nacelle and thus might be in-cloud and facing ice accretion while the nacelle is still below the cloud base or above the surface fog and not affected by icing. Second, the tip of the rotor blade has a different shape and it experiences much higher flow velocities and more vibrations than a stand-still instrument on the nacelle. For a safe and efficient operation of wind turbines under icing conditions, measuring rotor icing is thus mandatory.

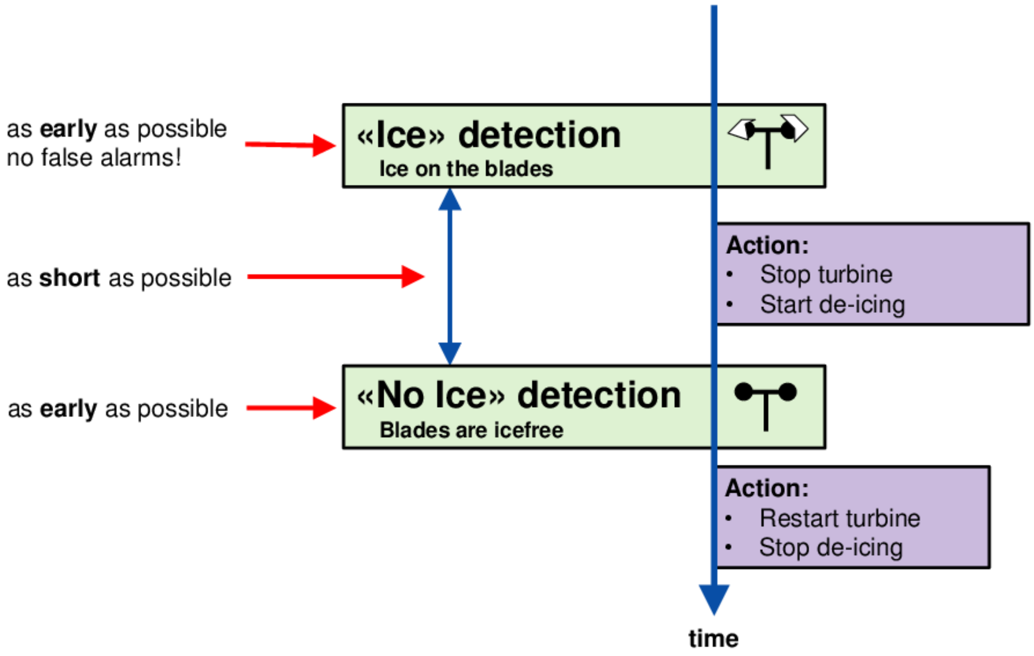

Figure 3: Illustration of a system for detecting "ice" and "no ice".

3 Evaluated systems

The following approaches and systems were evaluated in this study:

3.1 Nacelle based approaches and systems

- Temperature & relative humidity
- Heated versus unheated anemometer
- Combitech IceMonitor (SWE)
- Goodrich 0871LH1, 0872F1 and 0872E3 (USA)
- Holooptics T41 and T44 (SWE)
- New Avionics Ice Meister Model 9734 (USA)
- Labkotec LID-3300IP (FIN)
- Leine Linde Systems IPMS (GER)
- Meteorological Monitoring System PMS (CZE)
- Sommer Messtechnik: IDS-10 (AUT)

3.2 Blade based approaches and systems

- Power curve and pitch angle
- Bosch Rexroth BladeControl (GER)
- Eologix (AUT)
- fos4X fos4IceDetection (GER)
- Wölfel SHM.Blade / IDD.Blade (GER)

3.3 Systems not manufactured anymore

- Hainzl Haicmon$_{ice}$ (AUT, blade based)
- Infralytics (DE, blade based)
- MOOG Insensys RMS (UK, blade based)

4 Evaluation of nacelle based approaches and systems

4.1 Temperature & relative humidity

4.1.1 Description of ice detection system/techniques

This method is based on identifying meteorological conditions which allow meteorological icing. Icing is detected when the measured temperature and relative humidity exceed given predefined threshold values. These are typically below 2 - 5 °C for air temperature and above 90 - 95% for relative humidity.

4.1.2 Measured parameters

Icing is mainly driven by air temperature, wind speed, liquid water content of the air and droplet size distribution. Small water droplets tend to be transported around a structure without hitting it and thus do not lead to meteorological icing although the relative humidity is above the threshold. During meteorological icing, the criteria of temperature below 2-5 °C and relative humidity above 90-95% are always fulfilled.

However, there are many situations where the criteria are fulfilled but no meteorological icing occurs. The method thus results in false positive signals and therefore leads to a strong overestimation of the duration of meteorological icing. Instrumental icing and rotor icing cannot be measured with this method.

In addition, the radiation shield of unheated humidity sensors can get iced, resulting in a capture of humid air within the instrument and again in an overestimation of the duration of an icing event. Finally, measurements of relative humidity are mostly performed according to WMO/CIMO standards[5] where saturation water vapour pressure is always calculated with respect to water. Below 0 °C, saturation cannot be reached anymore using this procedure (Figure 4).

Therefore, the combination of temperature and relative humidity is not able to provide any of the required icing parameters.

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5 WMO/CIMO: Guide to Meteorological Instruments and Methods of Observation, Chapter 4, Annex 4.A, Item 17

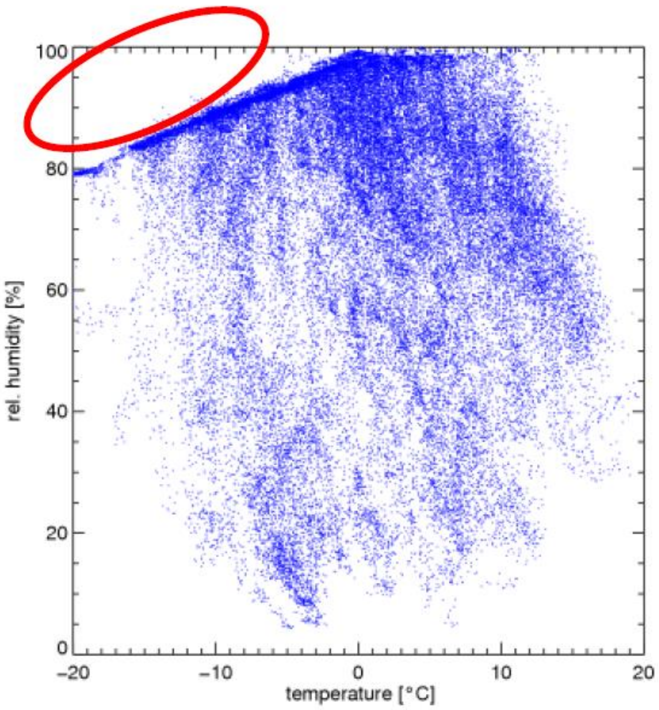

Figure 4: Relative humidity measured according WMO/CIMO standards does not reach saturation anymore at temperatures below 0 °C (red area).

4.2 Heated versus unheated anemometer

4.2.1 Description of ice detection system/techniques

Ice detection is based on observed differences in wind speed between an unheated and a heated anemometer. If installed at the same height, both anemometers should deliver similar wind speeds in the absence of ice. Once ice starts to build and the unheated anemometer freezes, the wind speeds recorded become lower or zero and the ratio of wind speeds measured by the unheated and the heated anemometer deviates from one. Often also additional parameters are used, such as the standard deviation of the wind direction which drops to zero when the wind vane becomes ice-covered.

4.2.2 Measured parameters

The method is able to measure start and end of instrumental icing. It does not give information on meteorological icing, rotor icing or ice loads. If a sequentially heated anemometer is used in addition, an estimate of the icing intensity can be provided.

4.2.3 Technical specifications, sensor position

Fully heated anemometers are available from the following manufacturers[6]:

- **FT Technologies (UK):** Fully heated ultrasonic wind sensor
- **Gill Instruments Ltd (UK):** WindObserver series with different sensor heating options
- **Metek GmbH (GER)**: Sonic series 2D and 3D ultrasonic wind sensors with optional sensor head heating
- **NRG Systems (USA):** IceFree Ultrasonic wind sensor and IceFree cup anemometers and vanes
- **Thies Clima (GER):** Ultrasonic Anemometer 2D, fully heated
- **Vaisala (FIN):** Fully heated WA25 cup anemometer and wind vane and WMT700 ultrasonic wind sensor
- **Lufft (GER)**: Ultrasonic wind sensor Ventus_UMB.

[6] Navigant Research, BTM World Market Update 2012

4.2.4 Available operational experiences

Operational experiences show that the method is a fairly robust way for the detection of instrumental icing during site assessment. It is also quite frequently used for wind turbine control. However, natural deviations from one in the ratio of wind speeds occur frequently and are often also attributable to local turbulence rather than icing. Finally, the threshold ratio for icing is selected individually, there are no standards available.

4.3 Combitech IceMonitor

4.3.1 Description of ice detection system/techniques

The IceMonitor from Combitech (Figure 5 and Figure 6) measures the weight of ice accretion on a freely rotating vertical steel cylinder, according to the ISO 12494 standard[7]. The instrumental icing period lasts as long as the ice monitor registers an ice load. Ice accretion on the cylinder leads to an asymmetrical shape of the rod. This induces rotation and thus cylindrical ice formation. This allows detecting ice in all wind directions.

The plastic bearing of the rotating rod is electrically heated to minimize friction and to avoid icing on the bearing in order to ensure the free rotation. The housing of the load cell is also heated. The load cell is connected to an amplifier box that provides a standard output current loop which is proportional to the ice load.

The IceMonitor was originally developed for the use in a power line surveillance system. The instrument is therefore focused on the requirements of the power line industry, where cylindrical ice formation on a rotating conductor is a very common phenomenon leading to high additional loads.

The IceMonitor is designed for measuring high ice loads. High sensibility is not the main focus of the instrument. Turbine control is more in the need of fast and sensible icing event detection than ice load monitoring. The IceMonitor is therefore merely used to detect reasons for power losses due to icing or for wind farm site assessment.

7 ISO 12494:2001: Atmospheric Icing on Structures

Figure 5: Combitech IceMonitor without (top) and with ice accretion (bottom).

4.3.2 Measured parameters

The IceMonitor is capable of measuring start and end of meteorological as well as of instrumental icing at the vertical rod. It also provides information about the ice load and the icing intensity (icing rate) by means of the change of the ice load over time. It doesn't provide information on rotor icing.

The prototype was designed for a maximum ice load of 100 kg, and was later modified for lower maximum loads (10, 25 or 50 kg). Its current measuring range is from 0 to10 kg with accuracy of ±50 g. The versions with lower maximum loads, i.e. 10 and 25 kg, are also equipped with an internal, spring-based mechanical overload protection system.

4.3.3 Technical specifications, sensor position, power requirements

The cylinder is 30 mm in diameter and 0.5 m in length (ISO 12494). The surface area of the sensor is 0.05 m^2. The overall height of the sensor including the amplifier box is 1.15 m. The weight of the sensor including amplifier box and cable is 8.5 kg. The operating temperature ranges from -40 °C to +50 °C. The system has a built-in overload protection system based on springs. The sensor is hand-built for every customer.

The IceMonitor should be mounted at the top of a mast or similar. It does not need to be oriented to the wind.

The power supply voltage for heating and electronics is 10 to 36 V DC (nominal 24 V). The supply current is 1.2 A@ 24 V which is equal to approximately 30 W @ 24 V. The heating of the bearing is controlled by a thermostat. The heating is switched on if air temperature falls below 4°C and switched off if air temperature rises above 13°C.

4.3.4 Output signal, data transfer, data format

The output of the load cell is connected to a precision amplifier and converted into a standardised output current loop of 4 to 20 mA. The amplifier box is connected to electrical power and to the data acquisition equipment.

To log the data from the IceMonitor, any kind of data logger with standardised current input (4 – 20 mA) can be used. To be able to perform testing of the instrument, a test relay is included that will activate an electrical unbalancing of the load cell at which the output signal will increase to 8 mA to indicate that acquired data are reliable.

The IceMonitor is zero adjusted and calibrated before delivery. If necessary an additional zero adjustment can be carried out.

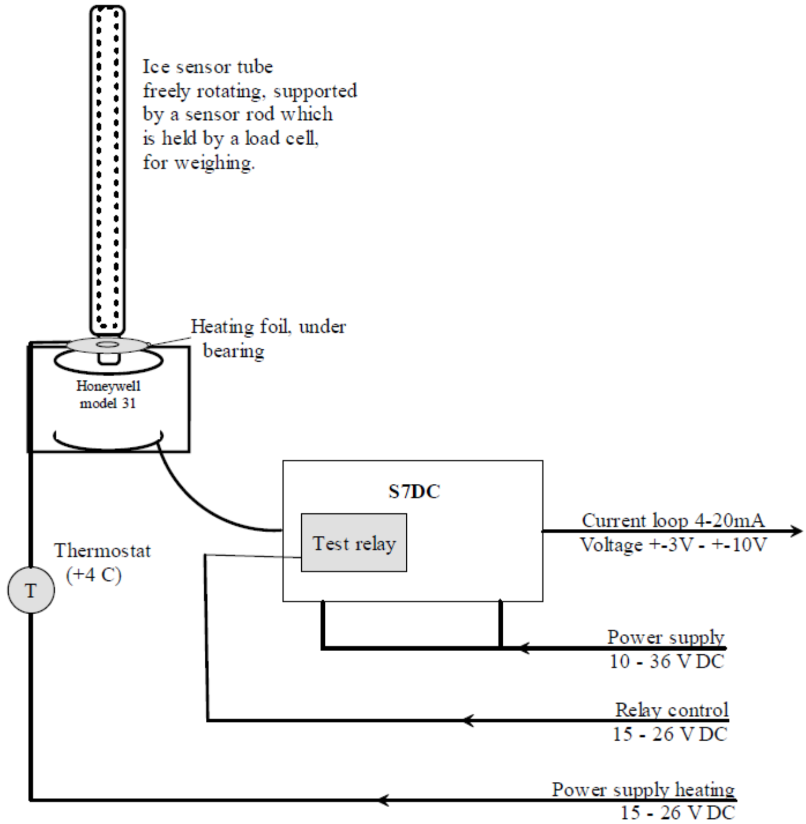

Figure 6: Combitech IceMonitor block diagram.

The IceMonitor is designed to work in harsh climate conditions at mountain tops. It is not tested in offshore conditions but according to the manufacturer, there is no reason why it should not work. All parts are of stainless steel or other rust-free material allowing for proper functioning under the presence of sea-salt.

4.3.5 Stage of development, technical maturity, available certifications

The first prototype was installed in Norway in 2003. The instrument has been commercially available since 2005. The first version Mark I was produced until 2009, which was then followed by Mark II. The Mark II was improved with a new amplifier with less temperature dependency, a new chassis with longer bearing supports that improved the sensor performance during strong winds, an improved heating that avoids the sensor from getting iced and a more stable load cell.

A new version with forced rotation and other improvements is planned but no release date or information on new features is currently publicly available.

The IceMonitor is compliant to the ISO 12494 specification for ice detectors (atmospheric icing on structures). The Combitech IceMonitor was tested in 2008 in an icing wind tunnel at the Kanagawa Institute of Technology in Japan.

The IceMonitor fulfills the EU EMC directives EN 50081, EN 50082 regarding electromagnetic compatibility.

4.3.6 Track record of manufacturer, size of company, no. of installed systems

Combitech AB is a large Swedish technical consultancy with 1,470 employees. Combitech Software AB was formed in 1992 and changed its name to Combitech Systems AB in 1999. In 2002 Combitech Systems became wholly owned by Saab. Combitech AB was then formed in 2006 as the result of a merger between Combitech Systems and parts of AerotechTelub.

Combitech is present in more than 20 locations in Sweden and Norway. The company is certified according to ISO 9001, ISO 14001, ISO 27001:2005 and TickIT.

The core expertise of Combitech is on information security, systems safety, logistics, systems integration, systems development, robust communications, technical product information and mechanical engineering and meteorological measurements. Icing measurements are representing a small part of the company.

Up to today, roughly 50 IceMonitor systems have been sold, mainly in Sweden (Table 2). Approximately 20 systems have been mounted on wind turbines. The IceMonitor is built by hand and on request.

Table 2: IceMonitor systems currently in use world-wide.

No. of pieces	Customer	Installation site	Date
5 pcs	Wind turbine supplier	Sweden	2010
8 pcs	O2 Vindkompaniet	Nationwide Sweden (Bliekevare, Sveg, Glötesvålen, Tåsjö)	2009-2010
1 pcs	O2 Vindkompaniet	Aapua, Sweden	2008
4 pcs	Elforsk	Sveg, Sweden	2008
6 pcs	COST Action 727	Germany, Finland, Sweden, Switzerland, Poland and Japan	2007
19 pcs	Varying customers		2006-2014

4.3.7 Available operational experiences, independent evaluations

Several independent benchmarks and inter-comparisons of the IceMonitor have been carried out:

- Intercomparison at five test sites in Europe in COST Action 727 between 2005 and 2009.
- Test at the met masts Fäboberget, Granliden and Blakliden in Sweden (Vindforsk V-363 project) between 2011 and 2013.

- Test at the sites Gütsch, Schwyberg and Matzendörfer Stierenberg in Switzerland from 2008 to 2010 (MEMFIS project).
- Test at the "Site Nordic Expérimental Éolien Corus" (SNEEC) in Canada between 2014 and 2015.

The main findings are the following:

- The measurement principle was found to be working and being able to detect icing.
- Due to the coarse accuracy of ±50 g, the sensor is not suited for measuring light icing events.
- A rather noisy output signal of the sensor, probably caused by wind induced vibrations, could be observed.
- The heating is not always capable of keeping the bearing ice free, leading to a disruption of free rotation. This has been seen in the field as well as in an icing wind tunnel test. Forming of an ice bridge between the fixed and the rotating part of the sensor can even lead to lifting of ice and negative values for ice load.
- It has been observed that the zeroing of the instrument is not stable over a longer period of time, leading to a drift in the output signal.

4.3.8 Other application fields of the system

The system is also used in power line applications.

4.3.9 References/Publications

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4.4 Goodrich 0871LH1, 0872F1 and 0872E3

4.4.1 Description of ice detection system/techniques

The Goodrich (formally Rosemount) 0871LH1 freezing rain sensor, and the 0872F1 and 0872E3 ice detectors (Figure 7) use an ultrasonic, axially vibrating probe to detect the presence of icing conditions. The sensing probe is a nickel alloy tube that has a natural resonant frequency of 40 kHz and is mounted in the strut at its mid-point with one inch exposed to the air-stream. In an icing environment, ice collects on the sensing probe. The added mass of accreted ice causes the frequency of the sensing probe to decrease. The ice load depends linearly on the induced frequency shift. The sensor software monitors the probe frequency and detects this decrease. If the frequency decreases below a predefined threshold, the internal probe heater power is switched on. The probe is heated to melt the ice until the frequency rises back to normal conditions. Once de-iced, the sensing probe cools within a few seconds and is ready to sense ice formation again. The ice detector output includes, but is not limited to, indication of ice detection and fault status.

The 0872F1 and 0872E3 detectors are designed to differentiate rain from freezing rain as temperatures approach freezing. The main difference between the models is the Baud rate. The 0871LH1 freezing rain sensor detects the presence of icing conditions and is used for wind energy as well as power transmission lines and towers, bridge applications and many others. The 0872F1 and 0872E3 models have a stronger heating than the 0871LH1 and are thus designed for heavier icing events.

Figure 7: Goodrich ice detector: left: 0871LH1 Freezing Rain Sensor, right: 0872F1/0872E3 Ice Detector.

4.4.2 Measured parameters

The Goodrich/Rosemount sensors are able to detect start and end of meteorological icing as well as the start of instrumental icing. They are not able to provide information on the end of instrumental icing or on ice loads. The frequency of heating cycles gives an indication on the icing intensity (icing rate). The ice detectors do not measure rotor icing.

According to the manufacturer, the 0872F1 and 0872E3 ice detectors are able to detect ice accumulations as low as 0.13 mm. The 0871LH1 freezing rain sensor provides a signal when ice accumulation reaches 0.5 mm.

4.4.3 Technical specifications, sensor position, power requirements

0872F1 and 0872E3 ice detectors

The probe is 6 mm in diameter and 25 mm in length. The dimensions of the electrical housing are 23 x 20 x 11 cm, and the dimensions of the sensing element and heat sink 16.4 x 17.3 x 11 mm. The total weight of the instrument is 5.7 kg. The operating temperature ranges from -50 °C to +50 °C.

The 0872F1 and 0872E3 models are mounted on a pole and are designed to operate continuously in an outdoor environment. The sensors do not need to be oriented to the wind.

The power supply voltage for heating and electronics 115 VAC, ±10%, 60Hz. In normal sensing mode, the power requirement is 10 W, while in de-icing mode it is 385 W.

Figure 8 shows an assembly drawing of the 0872F1 and 0872E3 freezing rain detectors.

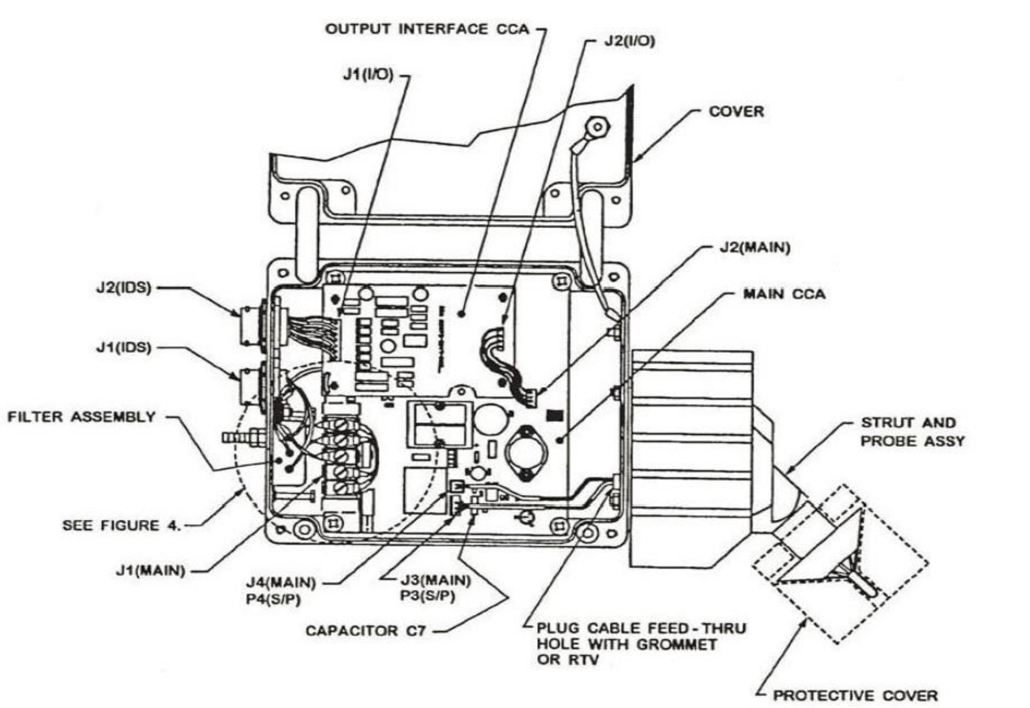

Figure 8: Assembly drawing of the 0872F1 and 0872E3 freezing rain detectors.

<u>0871LH1 ice detector</u>

The probe is 6 mm in diameter and 25 mm in length. The dimensions of the base are 7.32 x 3.81 cm and the dimensions of the strut are 3.1 x 2.54 cm. The total weight of the instrument is 0.3 kg. The operating temperature ranges from -55 °C to +71 °C.

The 0871LH1 model is mounted on a pole and is designed to operate continuously in an outdoor environment. The manufacturer recommends installing the sensor with an angle of 20 to 30° above horizontal. The sensor should be mounted facing the prevailing wind.

The power supply voltage for heating and electronics ranges between 22 and 29.5 VDC. In normal sensing mode, the power requirement is 15 W, while in de-icing mode, it is 50 W.

Figure 9 shows an assembly drawing of the 0871LH1 ice detector.

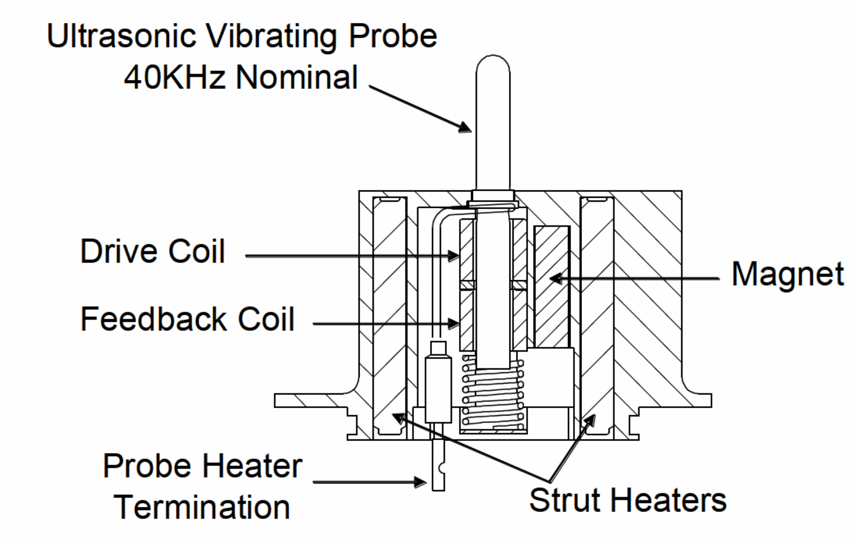

Figure 9: Assembly drawing of the 0871LH1 ice detector.

4.4.4 Output signal, data transfer, data format

<u>0872F1 and 0872E3 ice detectors</u>

The frequency changes at the probe associated to icing are communicated through an RS-232 or RS-232 current loop data link at 300 (0872E3) or 2'400 Baud (0872F1). The RS-232 configuration is 8 data bits, 1 stop bit, no parity, full duplex, configured as data terminal equipment (DTE). The maximum cable length is 30 metres.

The output signal is the ice thickness from 0-2.5 mm as well as the activity of the heater. It is possible to program the detector so that the heater only turns on if the temperature is below 5 degrees to avoid erroneous indications due to heavy rain and damage to the probe due to overheating.

The 0872F1 and 0872E3 require only periodic recalibration. No other maintenance is normally required.

<u>0871LH1 freezing rain sensor</u>

The frequency changes at the probe associated to icing are communicated through an RS-422 interface operating at 9'600 Baud as well as a discrete yes/no output. An RS-232 interface is available with line level converter.

The 0871LH1 requires only periodic recalibration. No other maintenance is normally required.

4.4.5 Stage of development, technical maturity, available certifications

The technology used in these sensors was first developed in 1966. There have been 9 iterations for land based icing sensors to date. The LH1 became first publicly available in 1994 and the F1 in 1995.

Today, only the 0872F1 and the 0871LH1 models are in serial production while the 0872E3 model is end of line. Since 2016 it is no longer possible to purchase the 0872E3 model.

The 0871LH1 was tested in 2008 in an icing wind tunnel at the Kanagawa Institute of Technology in Japan.

The instrument has been certified according to

- cTUVus by TÜV Rheinland of North America (Product Safety)

4.4.6 Track record of manufacturer, size of company, no. of installed systems

Originally, the ice detectors were developed and manufactured by the company Rosemount, USA. The instruments were designed for aircraft ice detection. Later the ice detection systems from Rosemount were taken over by the US company Goodrich and then by UTC Aerospace Systems Minnesota, USA. Today the instruments are manufactured by UTC Aerospace Systems Minnesota, still under the brand Goodrich.

In 2006, Campbell Canada took over the worldwide sales, service and promotion for all ground base applications for the Goodrich/Rosemount ice sensors.

Campbell Scientific was founded in 1974 in Logan, Utah. Today, Campbell Scientific develops increasingly powerful data loggers that have achieved worldwide use in environmental research and industrial markets for diverse applications. Campbell Scientific has established itself as a manufacturer of numerous related product lines for the measurement field, including a wide variety of sensors, as well as devices for the collection, storage, communication, and retrieval of data.

Today, affiliate offices operate in Australia, Brazil, Canada, China, Costa Rica, France, Germany, South Africa, Southeast Asia, Spain, the United Kingdom, and the United States. Campbell Scientific Canada has 74 and Campbell Scientific Europe 65 employees, respectively. Campbell Scientific Canada is an ISO 9001:2008 certified company.

Almost all wind energy applications use the 0871LH1 sensor and not the 0872F1/0872E3. Vestas and Alstom are large customers. 250 systems have been sold in 2014. Since Campbell Canada took over the sales, just over 700 total units have been sold.

4.4.7 Available operational experiences

Several independent benchmarks and inter-comparisons of the Goodrich ice detectors have been carried out:

- Intercomparison at five test sites in Europe in COST Action 727 between 2005 and 2009
- Test at the met masts Fäboberget, Granliden and Blakliden in Sweden (Vindforsk V-363 project) between 2011 and 2013
- Test at the "Site Nordic Expérimental Éolien Corus" (SNEEC) in Canada between 2014 and 2015

The main findings are the following:

- The measurement principle was found to be working and being able to detect icing. This was confirmed by the icing wind tunnel test in Japan.
- The Goodrich ice detector showed good performance, operating automatically during most of the time and being able to resist harsh climate.
- During severe icing events, the heating was not strong enough to remove the ice. This sometimes created igloos that completely hindered wind and ice from reaching the sensors. These circumstances can be overcome with different mounting techniques.
- In cases with low temperatures or snowfall, the sensor gets covered and cannot detect any ice. These circumstances can be overcome with different mounting techniques.
- Accretion of ice on the body of the instrument led to the build-up of an ice cover on the oscillating finger.

4.4.8 Other application fields of the system

The 0872F1 sensor is often used in AWOS (airport weather) stations across the USA and Canada.

4.4.9 References/Publications

- M. Wadham-Gagnon, N. Swytink-Binnema, D. Bolduc, K. Tété, C. Arbez, Ice Detection Methods and Measurement of Atmospheric Icing, IWAIS 2015
- H. Wickman, J.-Å. Dahlberg, P. Krohn, 2013, Experiences of different ice measurements methods, Elforsk report 13:15

- H. Wickman, Evaluation of field tests of different ice measurement methods for wind power, PhD theses, 2013
- S. Kimura, Evaluation of ice detecting sensors by icing wind tunnel test, IWAIS 2009
- R. Cattin, J. Rast, A Heimo, Y. A. Roulet, A test of the Goodrich 0871LH1 ice detector at the Guetsch station, IWAIS 2009
- S. Fikke, COST Action 727 WG2 – Review of Results, IWAIS 2009
- J. Rast, R. Cattin, A Heimo, Icing Indices: a good solution?, IWAIS 2009
- Cober et Al, Assessing the Rosemount Icing Detector with In Situ Measurements, Journal of Atmospheric and Oceanic Technology, Vol 18, 515-528.
- COST-727, Atmospheric Icing on Structures: 2006, Measurements and data collection on icing: State of the Art Publication of MeteoSwiss, 75, 110 pp.
- Campbell Scientific (Canada) Corp. (2011), “0872F1 Ice Detector”, Technical manual
- Campbell Scientific (Canada) Corp. (2009), “0872E1 Ice Detector”, Technical manual
- Campbell Scientific (Canada) Corp. (2014), “0872LH1 Ice Detector”, Technical manual

4.5 HoloOptics T40 series

4.5.1 Description of ice detection system/techniques

Two types of the HoloOptics sensors in the T40 series are suited for ice detection in wind energy applications: the T44 and the T41.

The HoloOptics T44 ice detector (Figure 10 and Figure 11) consists of four arms, equipped with infrared (IR) emitter-detectors, and a probe with an internal heating system, placed on the support structure in the centre. The diameter of the probe is 30 mm. The four arms emit IR signals on the reflective surface of the probe, which are then reflected back to the arms. During icing, the surface of the probe gradually gets covered by ice and the reflected fraction of IR decreases. An icing event is indicated when 85-95% of the surface of the probe is covered with 0.01-0.03 mm of ice. Then the heating system of the instrument is switched on. The heating is switched off again when the ice coverage of the probe has decreased to approximately 25%. The heating can be tuned to start and end with a programmable time delay.

The principle of function of the T41 sensor is the same, but the instrument consists of one arm only and therefore can measure icing only in a sector of ±45°. It is thus smaller in volume and weight. The T41 is recommended for use in cases where the wind direction causing icing is well known such as at the nacelle of a wind turbine. The T44 is recommended in all other cases as it can measure in all wind directions.

Figure 10: HoloOptics T44 (left) and HoloOptics T41 (right) sensor.

4.5.2 Measured parameters

The HoloOptics ice detector is able to detect start and end of meteorological icing as well as the start of instrumental icing. In normal mode, it is not able to provide information on the end of instrumental icing or on ice loads because the heating melts the ice away. The frequency of heating cycles gives an indication on the icing intensity (icing rate). It doesn't provide information on rotor icing.

Minimum detectable thickness of ice is 0.01 mm ± 0.001mm according to the manufacturer..

4.5.3 Technical specifications, sensor position, power requirements

The HoloOptics T41 occupies a volume of approx. 25 x 14 x 3 cm. The corresponding dimensions for the HoloOptics T44 are 50 x 25 x 25mm. The weights of HoloOptics T41 and HoloOptics T44 are 1.0 kg and 1.2 kg, correspondingly. The operating temperature ranges from -50 to +120 °C.

The HoloOptics T41 needs to be oriented in the wind whereas the HoloOptiocs T44 can measure icing in all wind directions.

The power supply voltage for heating and electronics ranges between 12 to 15 VDC, 15 V is recommended. In normal sensing mode, the power requirement is 2-3 W and in de-icing mode, it is 35-40 W. The heating power of the probe at 15 V is 5000 W/m^2.

On customer request, the sensor can be operated in a sleep mode to save power. If no icing measurement took place for one hour, the sensor is turned off, i.e. all heating and sensors are shut down. Once every 10 minutes the sensor is turned on for a short period. If no ice is detected, the sensor will go back into sleep mode for the next 10 minutes. If ice is detected, the sensor will switch to normal mode.

The sensor is designed to be used offshore but has never been tested in offshore conditions. It has no moving parts and the coat is made of stainless steel, which makes is suitable for offshore conditions.

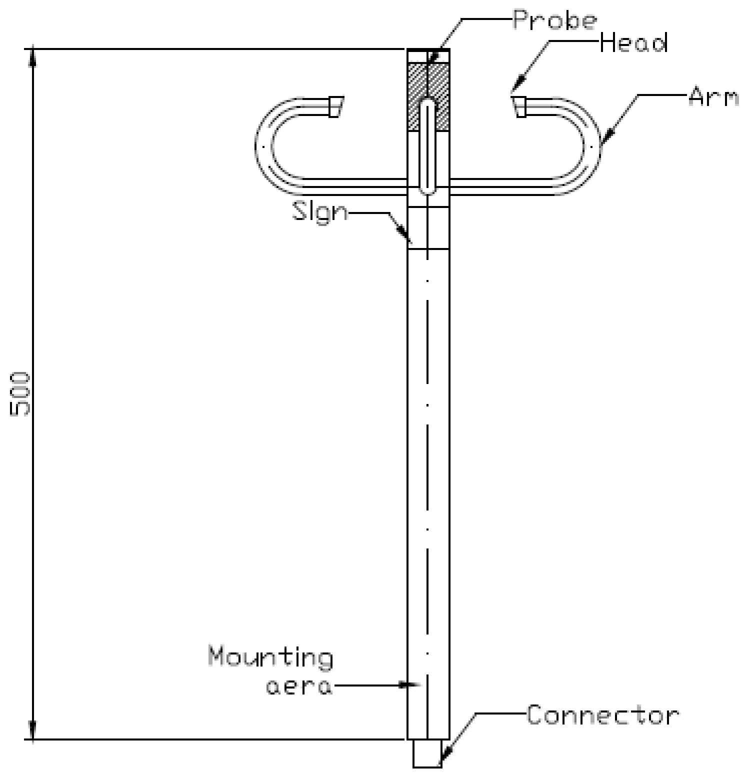

Figure 11: Technical drawing of the HoloOptics T44.

4.5.4 Output signal, data transfer, data format

The instrument provides a logic high signal when ice is detected. If indicating ice, the ICE signal is > 2.4 V otherwise, the ICE signal is < 0.6 V.

Data can be stored on all common memories. A network, a computer or a data logger connection is required for data transfer.

4.5.5 Stage of development, technical maturity, available certifications

The first test with prototype sensors was made in 2003/2004. The production of the HoloOptics T20 series started in winter 2005 and the HoloOptics T40 series in 2009.

The main improvements of the T40 series compared with the T20 series are:

- Higher de-icing capacity gives higher saturation level.
- Flexible threshold for icing alarm
- Overheating protection

- Improved status signal
- All external parts made of stainless steel

For the season 2015/2016, HoloOptics is planning an update of the T40 series (Mk 3). This update includes the following improvements:

- Selectable power supply voltage 12 or 24 V
- Ice signal and status signal selectable as 5 V or 12/24 V
- Improved resistance to false indications due to rain (Calibration made in a climate chamber at the Royal Institute of Technology, Stockholm, Sweden)
- Improved water-tightness
- Distinction between glaze and rime ice
- Use of the sensor as an ice warner: The icing signal is only activated, when the ice thickness exceeds a certain threshold.

The HoloOptics T26 was tested in 2008 and 2011 in an icing wind tunnel at the Kanagawa Institute of Technology in Japan. In 2009, the HoloOptics T44 was tested and calibrated in the icing wind tunnel at VTT, Finland. The sensor is not certified.

4.5.6 Track record of manufacturer, size of company, no. of installed systems

HoloOptics was founded in 1989 and is based in Sweden. During its first years the company was engaged in holographic interferometry. Many projects included double exposure, real-time and time-average holography. Today, HoloOptics develops, produces and markets high-quality customised measuring equipment using optical metrology, down to individual component level. HoloOptics today has two employees.

Approximately 15 instruments of the T20 series have been installed. Approximately 40 pieces of the T40 series instruments have been installed, around 20 of those are mounted on wind turbines.

4.5.7 Available operational experiences

Several independent benchmarks and inter-comparisons of the HoloOptics ice detectors have been carried out:

- Intercomparison at five test sites in Europe in COST Action 727 between 2005 and 2009 (T20 series)

- Test at the met masts Fäboberget, Granliden and Blakliden in Sweden (Vindforsk V-363 project) between 2011 and 2013 (T40 series)
- Test at the "Site Nordic Expérimental Éolien Corus" (SNEEC) in Canada between 2014 and 2015 (T40 series)

The main findings are the following:

- The measurement principle was found to be working and being able to detect icing.
- Erroneous indications can be produced under several weather conditions. Heavy intensity rain, wet snow, dew or fog can hinder the probe from reflecting back the IR and thus indicate false icing. The same can happen if the sensor is exposed to dust or if the IR ray path is interrupted by a disturbing object. If the detector is complemented with an air thermometer and a rain detector these erroneous indications can be identified and removed.
- During very heavy icing conditions, the sensor head and the probe remain free of ice due to an igloo of ice that is formed around the probe. In such situations no ice can be detected.
- Another source of error is the heating system which is prone to failures. A malfunctioning heating system can fail to remove all ice, thus indicating too high loads of ice.
- In the T20 series, water entering the housing led to instrument failure.

4.5.8 Other application fields of the system

The HoloOptics T42 with two sensor arms is designed for power lines applications

4.5.9 References/Publications

- H. Wickman, J.-Å. Dahlberg, P. Krohn, 2013, Experiences of different ice measurements methods, Elforsk report 13:15
- H. Wickman, Evaluation of field tests of different ice measurement methods for wind power, PhD theses, 2013
- S. Kimura, Evaluation of ice detecting sensors by icing wind tunnel test, IWAIS 2009
- S. Fikke, COST Action 727 WG2 – Review of Results, IWAIS 2009
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- R. Westerlund, HoloOptics, Is på vindkraftverk - Detektering, utbredning, personskaderiskminimering och produktionsbortfall, 2009, Elforsk rapport 09:06

- HoloOptics (2007), User guide, T40 series of Icing Rate Sensors, User Guide Edition 2.0

- Tech notes from HoloOptics:
  - Ice Sensor Mk 3
  - False indications
  - T40 Ice Warner
  - 2 colour sensor

4.6 Ice Meister Model 9734-SYSTEM

4.6.1 Description of ice detection system/techniques

The Ice Meister Model 9734-SYSTEM industrial ice detector is a commercial, general-purpose industrial ice sensor that monitors the optical characteristics of whatever substance is in contact with the acrylic, optical surfaces of the probe (Figure 12). Gravity removes liquid water, but ice sticks.

In non-icing conditions, liquid water is removed from the probe by gravity. Air is in contact with the probe. The parameters measured are opacity and optical index-of-fraction. The probe senses air, and reports "no ice". In icing conditions, water molecules bind together and accumulate on the optical surfaces as a solid, resisting removal by gravity. Ice is in contact with the probe. The probe senses ice, and the sensor reports "ice alert".

The sensor is a further development from an aviation ice sensor. It is a low cost and easy to install option for an ice warner (go/no-go) on the nacelle. This sensor has no specified accuracy, and is not intended to be used as an analogue measuring instrument of any kind. This sensor is to be used on the nacelle, or a tower cantilever, or a nearby meteorological tower.

Another sensor of the series, the Ice Meister 9732-PLASTIC, is designed for aircrafts and might be suited for blade tips. It requires electric wires in the blade, though, which poses a danger due to lightning. This issue is addressed by an energy-harvesting scheme and Bluetooth wireless data link.

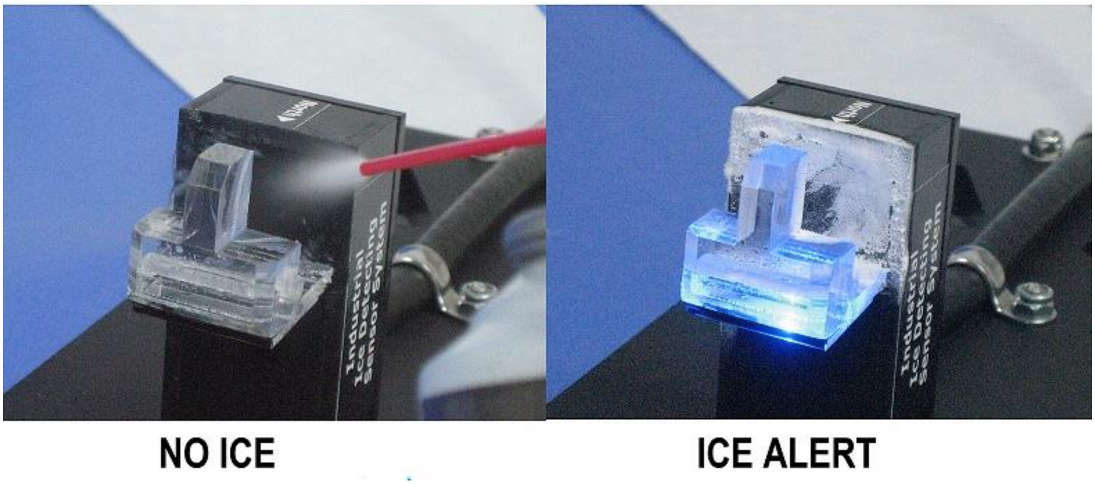


Figure 12: Ice Meister Model 9734 ice detector and an example of ice detected. It indicates ice alert with output relay contacts and a blue indictor LED.

4.6.2 Measured parameters

The sensor measures start and end of instrumental icing. It does not provide information on meteorological icing, rotor icing, ice load or icing intensity.

4.6.3 Technical specifications, sensor position, power requirements

The sensor contains a small embedded circuit board, an optical probe, a plastic housing, and a lightweight blue cable that connects to its host system.

The Model 9734 sensor indicates the presence of ice. An optional protective cage is available to help guard against falling debris. Various mounting options are available for diverse applications.

The dimensions of the sensor head are 63.5 x 31.8 x 25.4 mm (H x W x D). The probe extension from housing is 25.4 mm. The dimensions of the housing are 279.4 x 101.6 x 12.7 mm (L x W x T). The system weighs 113.4 g, exclusive mounting hardware.

The sensitivity of the ice detection is below 0.025 mm of clear ice. The operating temperature ranges from -40 °C to 50 °C. The system requires maximally 100 mA at 24 VDC, and accepts any clean DC voltage from 6 volt to 30 volts. It can be powered by a 5 W solar panel.

4.6.4 Output signal, data transfer, data format

The output format is logic (true/false). The probe turns blue to indicate that ice is present and relay contacts are closed. The electrical output is a set of a single-pole, single-throw (SPST), normally-open relay contacts, rated at 1 A, 50 V non-inductive. The relay is closed when frost is present and open when frost is absent.

4.6.5 Stage of development, technical maturity, available certifications

Aerospace version model 9732 sensor's ice formation and detection has been tested and documented at NASA Glenn Icing Research Tunnel in Cleveland, Ohio, according to a matrix of temperature, humidity, altitude, air speed, liquid water content, drizzle drop diameter, and air pressure. Test tunnel matrix and report available upon request.

Aerospace version Ice Meister Model 9732 operates in conformance with core paragraph 5.2.1.1.1 of SAE aerospace standard AS 5498 in lieu of any published FAA Technical Standard Order for in-flight icing detectors. Model 9732 is also listed in paragraph 4.11 of SAE aerospace information report AIR 4367A.

Ice Meister is protected under US patents. The new generation Ice Meister Model 9734 was released onto the market in 2014.

Ice Meister ice-sensing performance in 9732-model aerospace products conforms to de-facto specification AS 5498 as above, but the technology has not yet been certified in 9734-model industrial products.

4.6.6 Track record of manufacturer, size of company, no. of installed systems

Founded in 1996, New Avionics Corporation is a privately held firm that develops manufactures and markets ice, frost and precipitation sensors for aerospace, industry and retail applications. Main focus is on aviation.

The company is based in Florida, USA and has 1-10 employees.

4.6.7 Available operational experiences

There are no independent studies available on operational experiences with the Ice Meister Model 9734.

The series of ice sensors is used in aerospace and industrial applications. The sensors are in use by customers in North America, Europe and Asia.

4.6.8 Other application fields of the system

The Ice Meister Model 9734 is used in many kinds of industrial applications, such as wind turbines, HVAC cooling towers, radio and TV broadcast towers, oil and gas rigs, vehicular bridges and overpasses.

4.6.9 References/Publications

- Ice Meister Model 9734 Industrial Ice Detecting Sensor System, Technical Data Sheet, issued 1 October 2015.

4.7 Labkotec LID-3300IP Ice Detector

4.7.1 Description of ice detection system/techniques

The principle of function of the Labkotec LID-3300IP ice detector (Figure 13 and Figure 14) is based on ultrasonic vibrations of a wire which is wound around a flat oval aluminium sensor surface. The amplitude of ultrasonic vibration of the wire decreases when ice accumulates on the wire. When the amplitude of the ultrasound signal drops below a pre-set threshold, ice is detected and the heating of the sensor/wire is activated. The heating is turned off when the signal reaches a stop-limit and the heating has reached a predefined temperature. The heating power, cut-off temperature and ice alarm amplitude can be defined by the user. The oval shape of the LID/ISD ice sensor results in having multiple effective "cylinder" diameters. This allows detecting ice under different environmental conditions (droplet sizes, droplet speed etc.).

Figure 13: Labkotec LID-3300IP ice detector.

4.7.2 Measured parameters

The Labkotec LID-3300IP ice detector is able to detect start and end of meteorological icing as well as the start of instrumental icing. The frequency of heating cycles and the rate of change in signal amplitude give an indication on the icing intensity (icing rate). It is not able to provide information on the end of instrumental icing or on ice loads because of the heating system. If the heating system is deactivated, instrumental icing can be measured at the cost of meteorological icing and icing rate. It doesn't provide information on rotor icing. An estimated amount of rotor icing of about 1 cm on the leading edge upon ice detection by the Labkotec sensor has been simulated by the assuming the same icing conditions all over the swept area of the rotor.

4.7.3 Technical specifications, sensor position, power requirements

Labkotec LID-3300IP ice detector consists of LID-3300IP Control Unit and LID/ISD Ice Sensor.

The LID/ISD ice sensor has a flat oval form which measures 35 x 10 x 2.5 cm (H x W x D) and is made of aluminium. The weight is 1.3 kg (1.7 kg with the standard mounting kit). The LID-3300IP Control Unit has the dimensions 125 x 175 x 75 mm and a weight of 800 g. The operating temperature ranges from -40 ºC to +60 ºC. The maximum operating altitude above sea level is 3,000 m (LVD directive for minimum distance of wires). Lightning protection is available when the sensor is mounted on wind turbines.

The detector is capable of detecting icing in all wind directions but mainly in the direction perpendicular to the surface of the sensor. The sensor should be mounted against the wind so that there is free airflow in front of the sensor. Free air distance must be minimum 5 m.

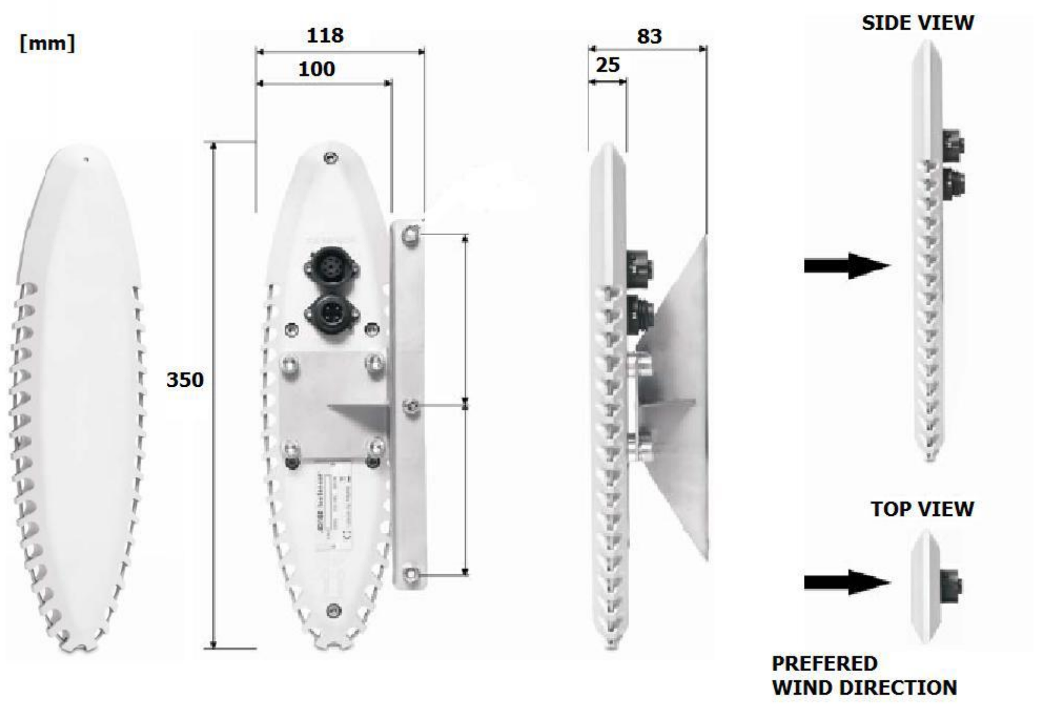


Figure 14: The LID/ISD ice sensor shown in different angles. From left to right: front, back, side, side and top view with preferred wind direction.

The power supply required is 230 VAC±10% at 50/60 Hz. The normal power consumption is 7 VA. The sensor body includes a 350 W heating resistor for de-icing of the sensor. In the USA and Canada the product is intended to be installed with a 230 VAC wind turbine power system only.

One temperature sensor is located in the centre part of the sensor, another temperature sensor inside the connector of the sensor cable. A safety thermostat is mounted inside the body of the sensor to break the heating circuit if the sensor temperature rises above +65 °C.

4.7.4 Output signal, data transfer, data format

The primary output signals of the LID-3300IP Ice Detector are potential free relay outputs for indication of ice alarm and fault. The sensor is also equipped with an RS-232 serial communication interface for configuration and connection to Supervisory Control and Data Acquisition (SCADA) systems as well as a built-in web server which provides a user interface for reading ice detector measurement data, status and parameters over the Internet as well as for modifying the sensor settings and reading a log file of alarms, faults and parameter changes. Access to the web interface is password protected with different user levels from visitor to administrator.

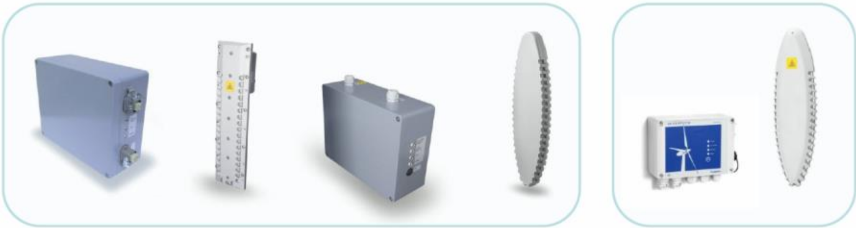
Additionally, an analogue signal (4-20 mA) for icing and temperature can be obtained directly from the control unit.

The instrument allows a variety of user settings:

- amplitude of ice signal in sensing mode (no ice)
- ice alarm level (threshold for producing the alarm signal)
- delay of ice alarm when ice alarm level is reached
- delay for ice alarm deactivation (prevent multiple alarms for same event)
- disable heating
- heating temperature, time, extension time, cooling time and more
- automatic sensor heating without an ice alarm in case of very light and long-term icing conditions

4.7.5 Stage of development, technical maturity, available certifications

The first prototype of a blade-mounted ice detector was delivered by Oy Labko Ab (nowadays Labkotec Oy) in Finland, Pyhätunturi, 1994. Serial production of the Labkotec LID-3210C started in 2002. The current version LID-3300IP of the LID sensors became available in 2010 (Figure 15).



	LID-3210C **Control Unit and Ice Sensor**	**LID-3210D** **Control Unit with** – Ice Alarm LED – Test button	**LID/IS** **Ice Sensor** – Sensitivity improved		**LID-3300IP Control Unit** – Web server (remote access) **LID/ISD Ice Sensor** – Sensitivity further improved
1994 ->	2002..2008	1Q/2008...2014	4Q/2008..2014		1Q/2010..

Figure 15: Development stages of the Labkotec ice detector.

The shape of the sensor in its current form has been established based on Computational Fluid Dynamics (CFD) modelling and Ansys simulations in the year 2010.

In 2011, a pre-certification of Labkotec LID-3300IP ice detector for wind energy applications has been carried out at the VTT icing wind tunnel.

In 2013, the LID-3300IP has been certified by TÜV Rheinland of North America Inc. according to the following American National standards regarding "Safety Requirements for Electrical Equipment for Measurement, Control, and Laboratory Use" (CU 72131267 01):

- UL 61010-1:2004 R10.08
- IEC 61010-2-010:2003
- CAN/CSA-C22.2 NO. 61010-1-04+GU1 (R2009)
- CAN/CSA-C22.2 NO. 61010-2-010-04 (R2009)

In 2014, the LID-3300IP has been certified by GL Renewables Certification (GL RC) concerning the design, the implementation of the design requirements in production and erection (IPE), the prototype testing and the manufacturers' quality system according to the normative reference GL Rules and Guidelines – IV Industrial Services – Part1 – "Guideline for the Certification of Wind Turbines", Edition 2010. The component certificate is valid until 2019-11-20 (CC-GL-013A-2014).

The following vibration tests of the sensor have been carried out in 2014 by VTT Expert Services Oy. Tests were carried out to both sensor and control unit:

- Sinusoidal vibration, IEC 60068-2-6, Test Fc (2007-12)
- Vibration, broad-band random, IEC 60068-2-64, Test Fh (2008-04)
- Shock, IEC 60068-2-27, Test Ea (2008-02)

The sensor is conforming to the requirements of the EMC directive 2004/108/EY and the Low-Voltage directive (LVD) regarding Electromagnetic Compatibility.

Functional safety properties of the Ice Detector LID-3300IP and LID/ISD sensor have been evaluated during 2014 and amended during 2015 together with VTT Expert Services. The evaluation is made in accordance with standard ISO 13849-1.

A new release of LID-3300IP will be available during 2016. It will further increase the functional safety performance level of the system and it will have improvements e.g. in the software upgrade procedure.

Labkotec is currently working on a new ice detector for wind turbine blades. Tests have been going on since 2011 at following locations:

- In-house icing laboratory
- Weather chamber
- Icing wind tunnel
- Met mast and station
- Wind turbines

4.7.6 Track record of manufacturer, size of company, no. of installed systems

Labkotec Oy is a leading Finnish manufacturer and supplier of electronic measuring technology such as high-precision level gauges for tanks and silos, leak detection systems for liquid containers, and alarm devices for oil, grease and sand separator, automation and detector technology, PC- and web-based remote monitoring systems and ice detection systems for critical installations in extreme weather conditions.

Labkotec was founded in 1964, specialising in measuring technology. The original name of the company was Oy Labko Ab. Labkotec Oy has been operating as an independent limited company since August 2007, as part of the international Indutrade Group. Today, the company has 50 employees, 10 of whom are working on ice detection systems.

The company is certified according to ISO 9001 and ISO 14001.

Over 3,000 systems have been installed in total, almost all of them on wind turbines, all over the world, and on almost all types of wind turbines. Labkotec ice detectors have been in use for more than 80 million hours cumulative.

4.7.7 Available operational experiences

Several independent benchmarks and inter-comparisons of the Labkotec ice detectors have been carried out:

- Test at the met masts Fäboberget, Granliden and Blakliden in Sweden (Vindforsk V-363 project) between 2011 and 2013 (LID-3300IP)
- Test at the "Site Nordic Expérimental Éolien Corus" (SNEEC) in Canada between 2014 and 2015 (LID-3300IP)
- Tests at the Hyytiälä meteorological mast, Finland 2014 (LID-3300IP)
- Tests at the Puijo meteorological station, Finland 2009-2014 (LID-3300IP)
- Test at the site Sternwald in Austria from 2002 to 2004 (LID-3210C)

The main findings are the following:

- The measurement principle was found to be working and being able to detect icing. This was confirmed by icing wind tunnel tests by VTT, Finland.
- The usability and reliability of the instrument has been found to be good. It is also easy to get acquainted with and the parameters are easy to adjust to adapt to different climates.
- The ice detector has been found to sometimes suffer from snow or precipitation induced false icing indications.
- During very severe icing events, the heater was not strong enough to keep the instrument ice free.
- Adaption of the user settings to given use cases and site-specific conditions seems to significantly improve the results.

4.7.8 Other application fields of the system

The system can be employed at airports and met-masts as well.

4.7.9 References/Publications

- M. Wadham-Gagnon, N. Swytink-Binnema, D. Bolduc, K. Tété, C. Arbez, Ice Detection Methods and Measurement of Atmospheric Icing, IWAIS 2015
- H. Wickman, J.-Å. Dahlberg, P. Krohn, 2013, Experiences of different ice measurements methods, Elforsk report 13:15

- H. Wickman, Evaluation of field tests of different ice measurement methods for wind power, PhD theses, 2013
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- Labkotec Indutrade Group, “LID-3300IP Ice Detector - Installation and Operating Instructions”, 2014
- GL Renewables Certification CC-GL-013A-2014
- TÜV Rheinland of North America Inc Certification CU 72131267 01
- Declaration of Conformity EMC directive 2004/108/EY and Low-Voltage directive (LVD) by Labkotec, 2014

4.8 Leine Linde Systems IPMS

4.8.1 Description of ice detection system/techniques

The Leine Linde Systems IPMS ice prevention and monitoring system (Figure 16) detects meteorological icing based on measurements of temperature and relative humidity. The potential of icing is detected when a given threshold of air temperature and relative humidity is exceeded, typically below 2-5 °C for air temperature and above 90% for relative humidity. When these conditions occur, an alarm is sent out automatically. The installed 360° swivelling camera system then allows the operator to check the current situation on the site via video live stream and to make the necessary decisions such as stopping a wind turbine or activation of a de-icing system. Alternatively, the turbine can be stopped automatically by the IPMS system.

When the conditions for meteorological icing based on air temperature and relative humidity are no longer given, the icing alarm is deactivated and the operator is informed automatically. Again, the operator can check the current situation on the site through the camera system and make the necessary decisions such as a restart of a wind turbine when the blades are ice free or de-activation of a de-icing system.

During the night, a remotely controlled spotlight (discharge lamp, 70 W) enables the camera system to take pictures as well.

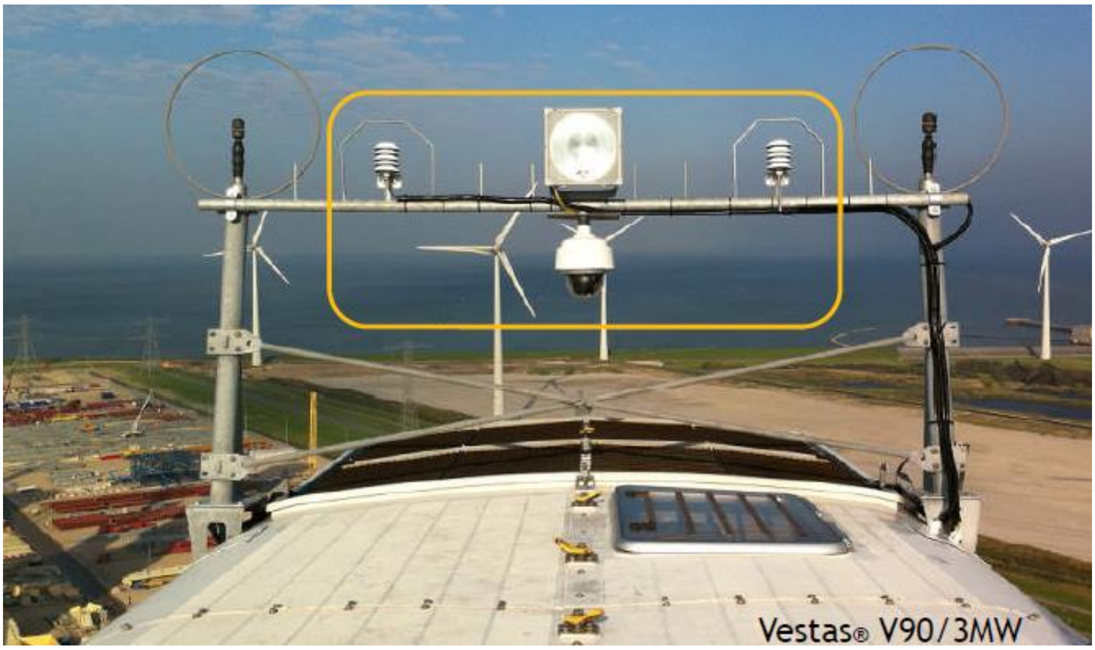

Figure 16: The Leine Linde Systems IPMS ice prevention and monitoring system: temperature and humidity sensors, spotlight and the webcam.

4.8.2 Measured parameters

This instrument measures air temperature and relative humidity which is then also converted into dew point temperature. This information is used to produce an ice warning and an ice alarm signal. Main goal is to identify icing conditions before ice actually starts to accrete on the blades. Optionally, rain rate can be measured as well to identify freezing rain.

Because of the inaccuracy of the ice detection approach with temperature and relative humidity (see chapter 4.1 for details), the system provides only information on the potential of meteorological icing.

With the 360° swivelling camera system, nacelle and blades can be inspected manually on instrumental/rotor icing and weather conditions on the site, given that the (visibility) allow for an undisturbed sight.

4.8.3 Technical specifications, sensor position, power requirements

Temperature and relative humidity are measured with two (Version 2.0: three) heated EE33 humidity / temperature transmitters by the company E + E Elektronik. The radiation shield itself is unheated. The operating temperature ranges from -40 °C to +60 °C for the temperature sensors and from -50 °C to +50 °C for the network camera. The network camera is placed in an air-conditioned dome.

The dimensions of the system (Figure 17) are as follows (W x H x D):

- **Control cabinet**:
  - V1.0: 400 x 400 x 210 mm
  - V2.0: 500 x 400 x 210 mm
- **Webcam**: 232 x 248 mm
- **Spotlight**: 385 x 310 x 160 mm
- **Connection box**:
  - Standard version for normal climate: 350 x 300 x 160 m
  - Cold Climate version: 500 x 300 x 160 m

The required power supply is 230 VAC at 50 Hz or 110 VAC at 60 Hz. The power consumption for the complete system is 400 W and 900 W for the cold climate version (IMPS 2.0).

All connections are placed inside a compact cabinet (Figure 18) for installation in the nacelle, including integrated PLC and main switch.

The sensor system can be designed for offshore conditions with special coatings.

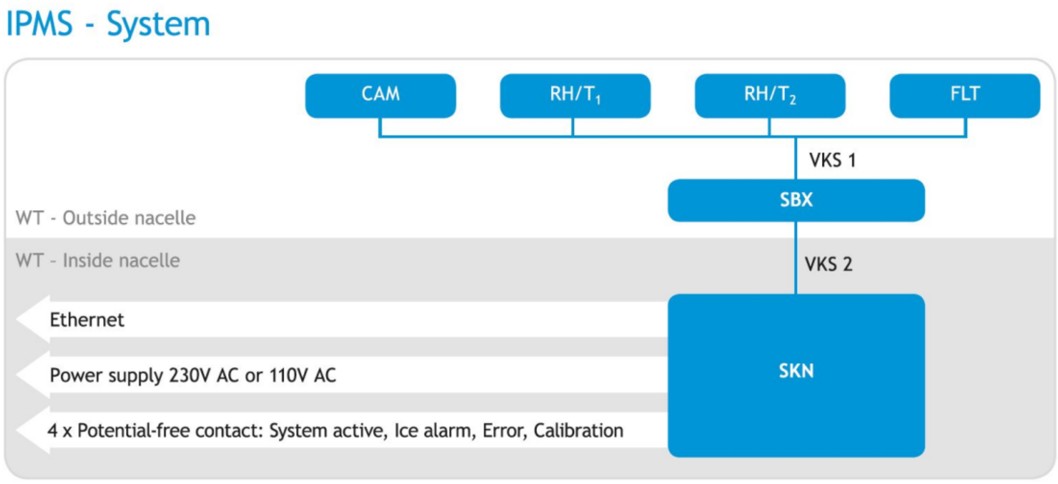

Figure 17: Block diagram of the Leine Linde Systems IPMS ice prevention and monitoring system.

Figure 18: Cabinet of the IPMS system inside the nacelle of a wind turbine.

4.8.4 Output signal, data transfer, data format

The system provides the following signals:

- System active (yes/no)
- Ice alarm/warning (yes/no)
- Error (yes/no)
- Calibration over the potential free contact

The ice alarm/warning can either be sent to the operator as an e-mail notification and/or directly be used for an automatic shut down the wind turbine.

The IPMS system offers the following electrical connections:

- Connection to WT control unit: 2 x changeover contacts, floating
- Connection of external sensors: 1 x analog, 4–20 mA, 1 x digital
- Ext. communication protocols: Modbus, OPC possible

The camera images/live stream and the measurement values can be accessed via internet /VPN tunnel) from anywhere. Inside the wind turbine, the camera system requires a DSL/Network connection with >8 Mbit/s for good camera functions, otherwise only photo mode is possible. 3G or 4G mobile image transmission is possible, depending on the location.

4.8.5 Stage of development, technical maturity, available certifications

The first system was installed in 2010 as IPMS Version 1.0. At the Husum wind fair 2015, the IPMS Version 2.0 was released with the following new features:

- Industrial manufacturing inside the Heidenhain group
- A third sensor for temperature and humidity as a reference sensor to follow IEC 13849 functional safety
- A new LED-spotlight
- Cabling connection between sensor box (outside nacelle) and cabinet is new pluggable for fast and easy installation
- Sensor box will be available in a cold climate version (with more powerful heating inside) and a standard version
- Surge protection against lightning or overvoltage

Certification of the system is in process.

4.8.6 Track record of manufacturer, size of company, no. of installed systems

Leine Linde Systems GmbH is a company based in Hamburg, Germany, with 9 other offices world-wide. It is a wholly-owned subsidiary of Leine & Linde Systems AB, Sweden – a long-standing and reliable partner for the wind power sector and a member in the Heidenhain group of companies. The Heidenhain group was founded in 1889. Leine Linde Systems GmbH was founded in 2012 and has today 9 employees at the headquarters in Hamburg and at the sales offices in wind markets all over the world.

Apart from the IPMS system, the main products of Leine Linde systems are the following:

- absolute encoders for pitch
- pitch, azimuth and slip ring
- incremental rotary encoders for measuring rotational speed
- magnet ring rotary encoders for large shaft diameters
- slip rings for power, signal and data transmission
- non-contact rotary joints for maximum data transfer
- pitch motors with minimal reaction times
- sensors for condensation, temperature and humidity

Leine Linde systems is a member of the Bundesverband Windenergie and the European Wind Energy Association.

The first ice detection system was installed in 2010. Currently approximately 40 IPMS 1.0 systems are installed in the field in Germany, the Netherlands and Belgium on the following wind turbine types:

- REpower/Senvion MM82, MM92
- Vestas V80, V90, V112
- Nordex N100, N117
- Enercon E70, E82
- EWT 52/54
- Siemens D3

The first installations of IPMS 2.0 systems took place in 2015 in Czech Republic.

Leine Linde Systems has a licence agreement with the Dutch company Topwind about the IPS/IPMS rights. Topwind has the rights to manufacture and to sell the product IPS in Benelux countries. Leine Linde Systems is manufacturing and selling the IPMS in the rest of the world.

The temperature and humidity probe itself (EE33) is installed in over 1,200 locations worldwide, mainly in traffic engineering and chemical industry.

4.8.7 Available operational experiences

There are no independent studies available on operational experiences with the IPMS system.

It is known from existing studies, that ice detection based on temperature and humidity alone tends to overestimate the icing frequency because of two reasons (chapter 4.1): First, measurement of relative humidity below 0°C is uncertain and second, ice can build at the radiation shield of the thermometer. This method thus can lead to excessive downtime or heating of turbines if intended to be used automatically.

4.8.8 Other application fields of the system

None.

4.8.9 References/Publications

- Leine Linde Systems company brochure
- Leine Linde Systems (2014), IPMS Ice Prevention for greater safety and higher energy yields, Specification sheet
- Leine Linde Systems, Präventive Eiserkennung mit IPMS, presentation by Jürgen Millhoff

4.9 Meteorological Monitoring Station PMS

4.9.1 Description of ice detection system/techniques

The ice detection system is an integral part of a meteorological monitoring station, called PMS. It includes a load sensor, situated in the body of the instrument that measures ice on a rigid (non-rotating), vertical rod of a length of 0.5 m and a diameter of 30 mm. The rod is attached to the bottom of the body. The bottom of the body is heated to prevent ice from sticking the body and the rod together when icing occurs. The heating parameters, threshold of ice load to start the heating (kg/m), length of the heating period (min) and the heating interval within the heating period (min), can be set by the user.

Along with ice load, the PMS system monitors the meteorological parameters temperature, wind speed and direction and relative humidity. The PMS system is developed for monitoring icing of overhead electric lines. It gives a warning or an alarm when pre-defined thresholds for the monitored parameters are exceeded. The user can then decide on an action necessary to deal with the situation. Up to today, it has not been used for wind energy applications.

Figure 19: The meteorological monitoring station PMS with the support arm and the sensor with the vertical rod for measuring ice load, temperature and relative humidity. The green central box can be seen on the right.

4.9.2 Measured parameters

The following quantities are monitored by the PMS station: ice load, temperature, wind speed and direction, relative air humidity and, optionally, solar irradiance. The measured data are evaluated, archived and supplied to a control system. It can be assumed that the heating does not significantly influence the ice load on the rod.

The PMS system can measure the start and the end of meteorological icing, as well as instrumental icing at the vertical rod. It also provides information about the ice load and the icing intensity (icing rate) by means of the change of the ice load over time. It does not provide information on rotor icing.

The system can measure ice up to 20 kg, i.e. 40 kg/m. The resolution of the measurement is 0.01 kg, with an accuracy of 1 %.

The PMS station also provides meteorological measurements. The rod measures wind speed and direction in addition to ice load. A SHT15 sensor is used to measure temperature and relative humidity. Optionally, a Gill Windsonic ultrasonic anemometer can be provided for wind speed and direction measurements and Kipp&Zonen CMP3 pyranometer for solar irradiance measurement.

Figure 20: Installation of the PMS system on a high voltage substation.

The PMS station operates in two basic regimes:

- **Measuring regime:** It measures, processes and downloads the measured quantities ice load, temperature, wind speed and direction, relative air humidity and, optionally, solar irradiance.
- **Warning regime:** It generates and sends warning signals with transmitting them into the central computer – based on pre-set values. These values are established based either on the exceeding of the set limit for the instanta-

neous state of the quantity being measured or on the exceeding of the set limit for the trend of development of this quantity (e. g. the combination of the trend of icing growth with the instantaneous load of the ice deposit, etc.). The signalisation of foreign intervention into the station and the loss of supply voltage are also a part of warning signals. The limits for the transmitted measured values with the signalisation of their exceeding can be set, checked and signalised directly in the central computer as well.

The PMS station itself does not include any parts requiring regular maintenance. The constructional parts are made of either stainless steel or steel protected against corrosion by a zinc coating. The ice measurement should be periodically controlled for drifts. The ice load measurement fluctuates around zero during normal operation. If the drift exceeds the interval of 10,000, the icing should be calibrated back to zero kg/m. The temperature and relative humidity sensors are calibrated by the manufacturer. No other calibration is required. The irradiance sensor is recommended to be calibrated every two years. The solar panel should be cleaned every two years. The accumulator used for providing the back-up supply, is free of maintenance. The operational regime of the battery is controlled by the automatic system in the central box. The battery is charged via the charging controller that secures a permanent charging, protects against overcharging, prevents discharging through the photovoltaic module at time without sunshine and provides temperature compensation of the control voltage, depending on ambient temperature.

4.9.3 Technical specifications, sensor position, power requirements

The PMS station consists of two, optionally three, basic parts: 1) the central unit box including the accumulator, 2) the support arm with the sensors mounted on it and, optionally, 3) solar panels for power supply.

The dimensions of the sensor for ice load measurement are 240 x 820 x 240 mm (W x H x D). The rod has a length of 0.5 m and a diameter of 30 mm. The support arm with sensors has a length of one meter. The sensor for wind speed and direction measures 142 x 163 mm (∅ × H) whereas the sensor for irradiance measures 110 x 84 mm (∅ × H). The central box has the dimensions of 470 x 750 x 250 mm (W x H x D) and the solar panel 1007 x 652 x 36 mm (L x W x H).

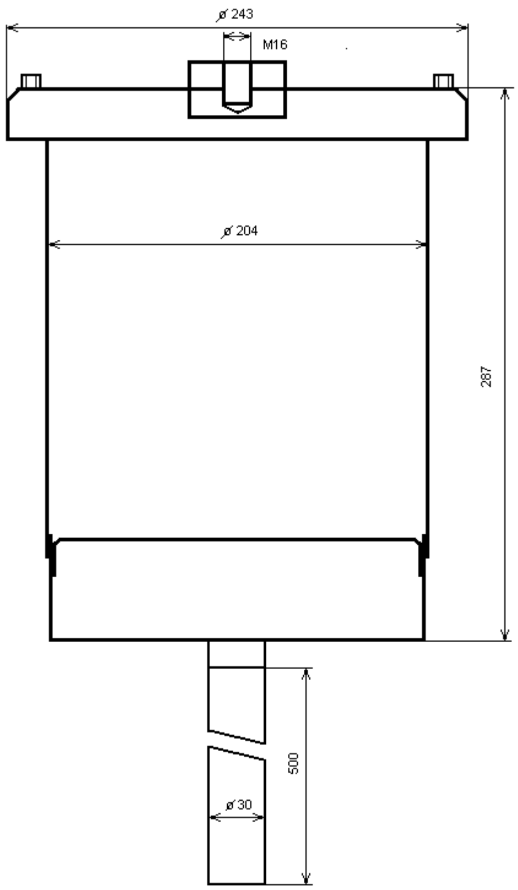

Figure 21: A sketch of the sensor for measuring ice load, temperature and relative humidity.

The weights of the individual components are:

- Sensor for ice load, temperature and humidity 10 kg
- Anemometer GILL WINDSONIC 0.5 kg
- Pyranometer CMP3 0.3 kg
- Central box 37 kg
- Accumulator (FIAMM 135 Ah – with solar panels) 46 kg
- Accumulator (Panasonic 2x17Ah – others) 8 kg
- Solar panels (2 pcs) 16.6 kg

The sensors are mounted to the support arm and the support arm to the tower with common screws.

The PMS system can be supplied with power in three ways: from the low voltage network, from the medium voltage network across a voltage transformer or via the solar panel. For the use on a nacelle of a wind turbine the solar panel is the most suitable means of supply. The solar system includes photovoltaic panels, a charging controller and the accumulator. The supply is secured by two photovoltaic panels Kyocera KC85GHT-1 with power output 87 Wp/12 V connected in parallel, with the total power output 174 Wp/12 V at irradiance 1000 W/m^2, combined with a maintenance-free accumulator FIAMM 12SP135 with the capacity C_{10} = 135 Ah. It is not recommended to activate the heating of the ice load sensor while supplying the PMS by solar power.

4.9.4 Output signal, data transfer, data format

The measured samples of meteorological quantities are processed each minute. Ice load, temperature and relative humidity are provided as 30-value averages per minute. Wind speed is provided as an average, an instantaneous and a maximum value of 30 measurements for every minute. Wind direction is given in an instantaneous and a maximum value. Average and instantaneous values are calculated for the irradiance.

The measured data are evaluated and then archived into daily files on the flash memory. The data can be sent instantaneously, or as daily files, to the control system (SCADA or a SQL server).

Ethernet is the standard interface for data transfer, with a possible extension to RS 422 (protocol IEC 60870-5-101). It is possible to communicate with the station remotely via GPRS using router or convertor to IEC 60870-5-104. Each PMS station is equipped with a SIM card.

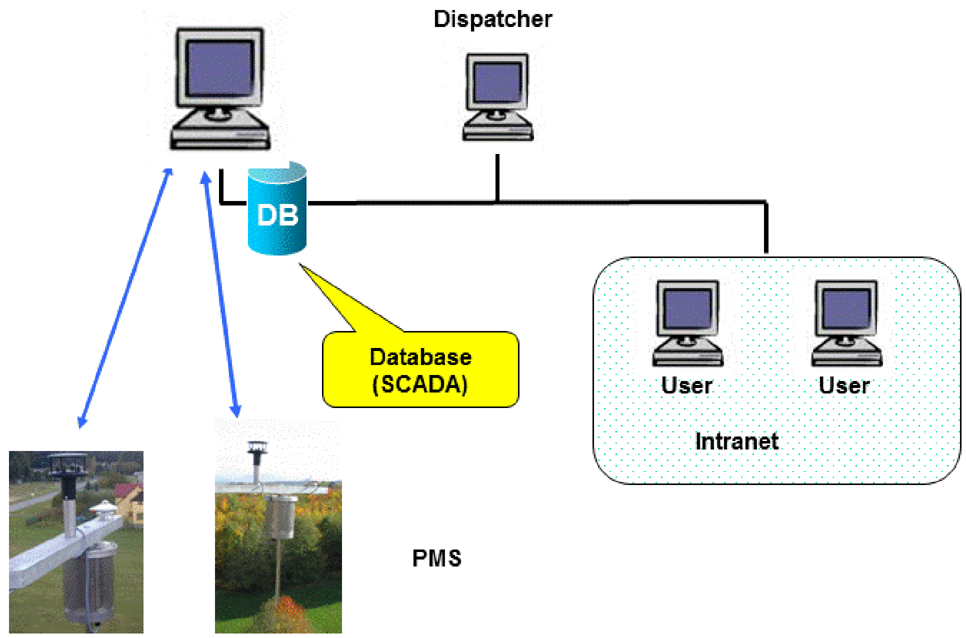

Figure 22: A scheme of processing the data measured.

4.9.5 Stage of development, technical maturity, available certifications

The first generation meteorological monitoring system, called Meteo, was developed in 1998-1999. Altogether 14 Meteo stations have been in operation. Two Meteo devices, installed in 1999 and 2003, respectively, were in use by the company CEZ (formerly known as VCE). The company E.ON (formerly JME) operated 12 Meteo stations during 2001-2002.

The development of the second generation system, the current PMS, started in 2006. It has new external sensors, can communicate via GPS and Ethernet and the power can be supplied by low and medium voltage lines or solar panels as opposed to high or ultra-high voltage lines.

The PMS system as such is not certified. The sensors used in the PMS system are certified by their respective manufacturers.

4.9.6 Track record of manufacturer, size of company, no. of installed systems

EGÚ Brno, a. s. is an independent company involved in the field of electricity and heat generation, transportation and storing. The EGÚ Brno, a. s. was founded more than 60 years ago. In 1950, the research team responsible for the high voltage technique of the Institute for theoretical and experimental electrical engineering of the Technical University in Brno (now VUT Brno) and a group of engineers from the study department of the then West-Moravian Power Utility (now JME Brno) were integrated into a new organisation: the Brno branch office of the Power Research Institute, seated in Prague. This organisation was one of several research institutions active in the Czechoslovak energy sector at that time.

In September 1951 all these institutions were consolidated into one organisation under the name Research Institute for the generation, distribution and utilisation of energy. With a seat in Prague, it had three branch offices in Brno, Bratislava (now Slovakia) and Tanvald. Later on this institute was re-named to Power Institute (Energetický ústav - herefrom the abbreviation EGÚ). In 1958, as a result of a profound restructuring of R&D basis, the institute received its initial name Power Research Institute.

The activities dealing with electric networks are focused on the problems of low voltage and medium voltage distribution networks and their operational reliability, on the effectiveness of investments, on designing new structures and assessing the loading conditions from the point of view of climatic effects. Within this responsibility the company provides consulting and expertise services, proposes new procedures and structures and is responsible for their realisation.

The present staff consists of 60 persons. The main customers of EGÚ Brno, a. s. are Czech and Slovak transmission system operators and distribution system operators.

By 2015, approximately 80 PMS systems have been installed (Table 3).

Table 3: PMS stations deployed

Company	State	Nr. of PMS installed	Location	Year or installation
ČEPS	Czech Republic	10+2	Lines 400 and 220 kV, substations 400/110 kV	2006-2007 (5), 2011 (3), 2012 (2), 2016 (2)
ENEL	Slovenia	1	Line 380 kV	2007
E.ON Distribuce	Czech Republic	19	MV lines	2012-2013 (18), 2015 (1)
E.ON Thüringen	Germany	13	MV lines & HV/MVsubstations	2008-2011
ZSE Distribuce	Slovak Republic	8	MV lines	2013
NKT	Germany	1	testing	2009
SEPS	Slovak Republic	1	400 kV line	2014
ČEZ	Czech Republic	4+20	MV lines	2015 (4), 2016-2017 (20)

4.9.7 Available operational experiences

Besides monitoring and processing meteorological data PMS stations have been implemented into a system which is used for calculation of dynamic line rating of some transmission lines by the Czech company CEPS. Furthermore, PMS stations are used as a source of actual meteorological data.

Field test have been carried out within COST Action 727 in the Czech Republic an in the UK. In all cases, the sensor seems robust and to be working reliably.

4.9.8 Other application fields of the system

The PMS monitoring system is developed for and used in overhead power line applications. It has not been installed on wind turbines so far.

4.9.9 References/Publications

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- Vaculik P., Rampl M., Automated icing monitoring system on the territory supplied by JME (in Czech), CK CIRED 2005, Tabor, Czech Republic
- COST 727 Atmospheric Icing on Structures: Measurements and data collection on icing: State Of The Art, December 2006
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- Sabata J., Zeman L., Icemeter tests at Studnice Station, IWAIS 2009, Andermatt, Switzerland
- Wareing B., Sabata J, Testing the PMS Icemeter at Deadwater Fell, IWAIS 2009, Andermatt, Switzerland
- Lehky, P., Sabata J., Zeman L., User guide for the meteorological monitoring station – PMS, Brno, March 2013
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4.10 Sommer IDS-10

4.10.1 Description of ice detection system/techniques

The IDS-10 Ice Detection Sensor (Figure 23) detects ice and freezing rain using an impedance measurement technology. It measures the change of impedance on its surface during ice accretion. It can differentiate between ice and water. It is a robust, non-contact and solid state measurement method.

Optionally, a temperature / humidity sensor can be added. With this sensor, the dew point, frost point and dew point spread can be determined. This additional measurement allows for a plausibility check of the ice detection.

The instrument is still under development and will be released to the market in 2016.

Figure 23: The Sommer ice detection sensor IDS-10.

4.10.2 Measured parameters

The sensor is heated automatically when ice is detected. It detects thus start and end of meteorological icing and the beginning of instrumental icing. The number and the frequency of heating cycles give an indication on the icing intensity/icing rate. The end of instrumental icing, ice loads or rotor icing cannot be measured.

For the standard sensor, the minimum thickness for detectable ice is 0.1 mm according to the manufacturer. A special aviation sensor used for ice condition on airports detects already a minimum ice thickness of 0.01 mm.

In addition, the IDS-10 also measures the ambient air temperature and humidity (optional equipment). Derived from these measured parameters the sensor also outputs the current frost and dew point as well as the air temperature and dew point spread (difference between air temperature and dew point).

4.10.3 Technical specifications, sensor position, power requirements

The dimensions and the weight are still to be announced. The operating temperature ranges from -40 °C to +80°C.

Supply voltage for the ice detection sensor is 10-30 V DC and for the heating unit 24 V AC/DC. Power consumption of the instrument in sensing mode is ca. 1 W @ 12V. In heating/de-icing mode it consumes 84W @ 12V.

The sensor has an integrated lightning protection and an integrated reverse voltage protection.

Currently there are no plans to develop a version suitable for offshore use. The sensor manufacturer, Sommer Messtechnik, has large experience with harsh mountain climate.

4.10.4 Output signal, data transfer, data format

The following output signals are available

- SDI-12 (Serial Digital Interface at 1,200 Baud)
- RS-485 (Modbus)
- Three relay outputs (rain, ice, failure)

The IDS-10 has several integrated features that help to monitor the status of the sensor. In addition to the supply voltage and the heating current measured, the sensor also outputs error codes to inform on the operational functions.

The threshold to start the heating can be parameterised depending on the thickness of the ice on the sensor plate.

4.10.5 Stage of development, technical maturity, available certifications

The sensor is still under development. In winter 2015/16, about 10 sensor systems are deployed at different field tests on airports, highways, wind stations and mountain peaks between 1,000 m and 2,000 m asl.

Winter 2015/16 is planned to be the last test season before making the sensor commercially available in 2016.

There are no certifications available.

4.10.6 Track record of manufacturer, size of company, no. of installed systems

Sommer Messtechnik is based in Koblach, Vorarlberg, Austria and was founded in 1987. Sommer Messtechnik develops and sells sensors and environmental monitoring equipment including system solutions for data recording, data transmission and analysis of the captured data.

Sommer Messtechnik is a specialist in hydrography, meteorology, industry and water management, sewage and geotechnical applications, innovative Doppler radar sensors for discharge measurement, unique snow monitoring technology as well as user friendly systems for data management and telemetry. Realising monitoring systems far from any infrastructure and in remote and harsh environments, such as alpine and high alpine weather stations, builds another field of expertise of Sommer Messtechnik.

Today, Sommer Messtechnik has 45 employees. In 2014, Sommer Messtechnik was certified according to ISO:9001.

4.10.7 Available operational experiences

The system is new and no operational experience is publicly available so far.

4.10.8 Other application fields of the system

The IDS-10 can be used for applications such as high-voltage power lines, overhead wires for railway and tram, icing on antennas, site evaluations for wind power plants, weather stations, controlled heating of meteorological sensors and antennas, scientific evaluation of icing conditions, road hazard warning systems and ice detection on airports.

4.10.9 References/Publications

- IDS-10 Product factsheet

5 Evaluation of blade based approaches and systems

5.1 Power Curve and Pitch Angle

5.1.1 Description of ice detection system/techniques

Presence of ice changes the aerodynamic properties of the blades and thus affects the power production. This effect can be detected with two methods:

- **Power production versus wind speed**: Deviations between produced power and power curve versus wind speed. This approach can be applied only when the wind turbine operates below rated power. An operational power curve which describes the power produced as a function of wind speed is created during periods of no icing (temperature above +2 °C). When the production deviates from the operational production according to the power curve, icing is detected.
- **Pitch angle versus wind speed**: Deviations between actual pitch angle to normal pitch angle according to wind speed. This approach can be applied when the turbine operates at rated power. Similarly to the power curve method, the pitch angle is monitored during normal operation without ice (temperature above +2 °C). Once the pitch angle deviates from the normal operation, icing is detected.

5.1.2 Measured parameters, additional data, calibration

Both methods detect changes of the aerodynamic properties of the blades, which can be caused by ice, among other reasons. Other reasons include dirt or defects on the surface. As long as ice is present on the blades, it can be detected. The methods are not able to provide information on meteorological icing, instrumental icing, ice loads or icing intensity.

The turbine has to be in operation for the ice detection to work. The method does not work at stand still or during idling.

The methods are capable of detecting ice anywhere on the blades because an increased mass due to ice anywhere on the blade will affect the aerodynamic properties of the blades and result in reduced production.

A calibration period is required. This is typically performed during operation while the outside temperature is above +2°C.

5.1.3 Technical specifications, sensor position, additional data required

Ice detection with the power curve method can be made without any additional installations.

These methods require access to SCADA data by definition.

5.1.4 Power requirements, output signal, data transfer, data format, software

The evaluation of the icing by the SCADA-data based methods can be made with the standard SCADA data.

5.1.5 Stage of development, technical maturity, available certifications

The power curve method is very popular among the wind park operators in all parts of the world. It has not been certified.

5.1.6 Available operational experiences

This method is well proven and found to be robust.

5.1.7 Maintenance and durability

These methods require no maintenance.

5.1.8 References/Publications

None.

5.2 BLADEcontrol (Bosch Rexroth)

5.2.1 Description of ice detection system/techniques

BLADEcontrol is a condition monitoring system which allows the detection of ice on the rotor blades. The BLADEcontrol system is based on the measurement of the natural oscillations of the turbine blades by highly sensitive 2-axis piezoelectric accelerometers. BLADEcontrol performs an analysis of the natural oscillation frequencies of the turbine blade, which change when the blade is damaged or has a greater dynamic load or gets heavier, for example when ice forms. The frequency deviations can be transferred to ice mass with a calibration procedure by attaching an artificial mass on a blade.

The ice detection functionality is part of a Condition Monitoring System.

5.2.2 Measured parameters, additional data required, calibration

The BLADEcontrol system detects rotor icing in terms of deviations of the eigenfrequencies. A transformation to ice thickness is possible either based on mathematical models or, more exactly, by a calibration procedure where a known amount of additional mass is attached to the blade.

Because the detection is based on blade vibrations, the method delivers information on the conditions on the whole blade. BLADEcontrol does not make a statement about the real ice load as the system is less sensitive at root of the blade than at the blade tip. A minimum of 20 kg of ice is required at the root while loads of less than 1 kg of ice can be detected at the tip. The BLADEcontrol signal is based on the most common ice distribution on the blades: on the leading edge of the blades and on the outer half only.

Ice detection is possible at standstill and during operation. A minimum wind speed of 2 m/s is required. There is no minimum rotation per minute (rpm) required. However, no evaluation is possible during idling since there is usually not enough excitation due to low wind speed. If the turbine is running, the spectrum is analysed in edgewise direction, whereas the flapwise direction is analysed when the turbine is stopped. "Ice", as well as "no ice", can be detected without putting the turbine back in operation.

The warning and alarm thresholds can be modified by the manufacturer if required by operational experiences.

The frequency deviation of a relevant vibration is recorded as well as the operational conditions and the transmitted signals.

A calibration period of three months is required for determining thresholds and the influence of the operating condition for ice detection for each new turbine type. The calibration of new turbines of well-known turbine types takes less than a week. The learning period and calibration needs to take place when there is no ice on the blades. This can be expected for measurements with a blade temperature above +5 °C. The customer receives a commissioning protocol after a successful calibration of the system.

Supply of real-time SCADA or controller data of power and pitch as well as overall operational status (normal operation, service mode) and environmental data (wind speed, temperature) is required to operate BLADEcontrol. The standard protocol is Modbus/TCP where many other protocols are supported.

5.2.3 Technical specifications, sensor position, power requirements

Figure 24 shows a schematic overview of the BLADEcontrol system architecture. The complete BLADEcontrol system consists of five components (Figure 25):

- **Sensor**: installed in the rotor blades (one per blade) and the hub to measure rotor blade and turbine oscillations
- **HMU (Hub Measurement Unit)**: hub processor to record measurement data and communicate with the ECU
- **ECU (Evaluation and Communication Unit)**: evaluation and communication processor to evaluate/process measurement data and communicate with the DBS
- **DBS (Database and Backup Server)**: database processor for communicating with the ECU, storing and handling persistent data, and managing communication with users
- **WebVIS (Web Visualisation System)**: web-based graphical user interface for visualizing current and previous conditions of a turbine's rotor blades. Usage is authorised based on access data (username, password)

The **Sensors** are 2-dimensional oscillation sensors with a temperature sensor included and a sensitivity 1,000 mV/g. The ICP-compatible voltage output allows long cables and has a very low EMI at rough environmental conditions. The sensing element is PZT Shear design, the housing die cast aluminum alloy. One sensor is 77 x 51 x 31 mm in size and weighs 194 g.

The manufacturer recommends installing the sensors at approximately one third of the blade's length, measured from the bulkhead. The sensors are cemented onto the blades with special gluten. No intrusion into the rotor blade - hub system is necessary. The electric and electronic systems are lightning protected. The BLADEcontrol ice detector can be retrofitted or mounted during manufacture.

The **Hub Measurement Unit (HMU)** is located in the hub of the wind turbine. The signal lines of acceleration sensors from the rotor blades and the hub sensor are connected to the HMU. Further analogue channels (e.g. for acquiring the pitch angle) are available. The HMU digitises all input signals under conditions of chronological synchronism and transmits them (normally via WLAN) to the Evaluation and Communication Unit (ECU) for processing. The HMU requires a power supply of 24 VDC and has a power requirement of typically 15W@24 VDC.

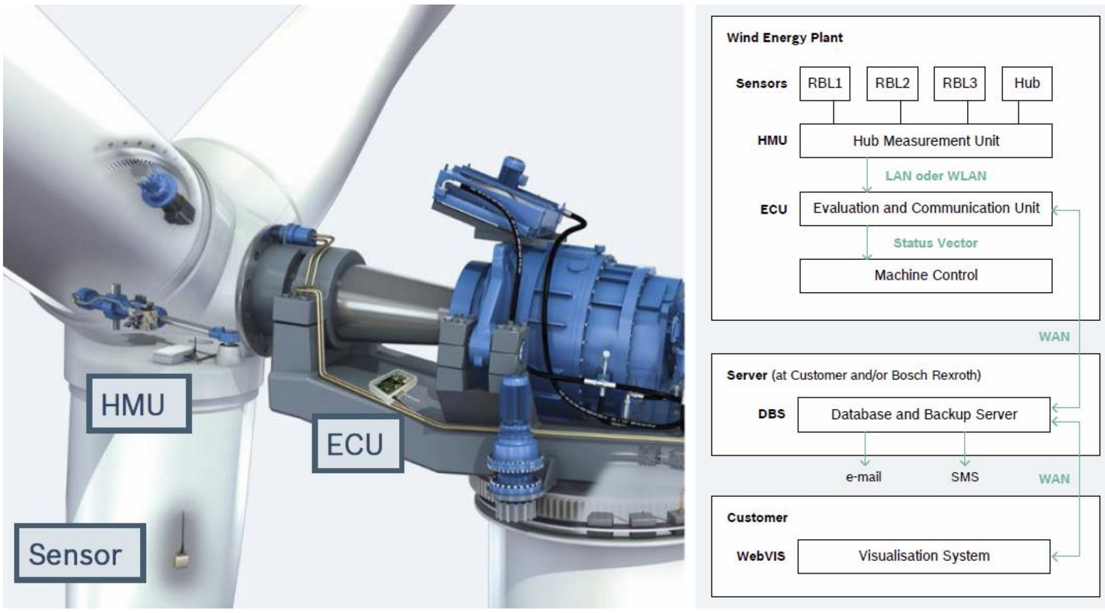

Figure 24: Schematic overview of the BLADEcontrol system architecture.

Figure 25: The components of the BLADEcontrol system.

The **Evaluation- and Communication Unit (ECU)** stores and evaluates measurement data transmitted by the HMU. Frequency-amplitude spectra are calculated from the amplitude time signal by the use of Fast Fourier Transformation (FFT). These spectra form the fundament for recognition of damages, overloads and ice deposits. Additional algorithms for damage detection are based on the evaluation of the raw time data.

The ECU is located in the wind farm. This can be inside of a wind turbine (tower, nacelle) or in another building. The primary measurement data is transmitted from the HMU. The ECU connects to the Database and Backup Server DBS over a second network to send measurement data and get updates of the ECU program and the reference database. The ECU requires a power supply of 24 VDC and has a power requirement of typically 19W@24 VDC.

Over the last 10 years a variety of several analogue and digital interfaces has been implemented to transmit the data between BLADEcontrol and the miscellaneous turbine controllers or SCADA systems.

5.2.4 Output signal, data transfer, data format, software

Internet connection is required for data transfer.

The BLADEcontrol system can be directly connected to SCADA system and interact with turbine control for an automatic stop or restart. The turbines receive a status vector via Modbus/TCP which can be used for turbine control. Provision of the BLADEcontrol status vector is achieved by a specified data protocol (Modbus/TCP).

The **visualisation component WebVIS** is used to illustrate the state of the rotor blade and details of the working state of the wind turbine. WebVIS can be accessed through a web browser. Furthermore historic data, mostly in intervals of an hour, or damage states out of these intervals can be viewed.

5.2.5 Stage of development, technical maturity, available certifications

The system has been available since the year 2005 and is in serial production.

The hardware of the system components has been updated in the past 10 years to ensure a long lasting system. With the growing experience about different turbine deviations and blade damages that can occur in real turbines the number of algorithms for the detection of abnormalities has increased.

A model with optically connected sensors will be available in 2017.

Different models adapted for wind turbine manufacturers have been developed.

Available certifications are:

- GL – Energy Renewables Certification: Type Certificate BLADEcontrol Ice Detector BID. GL Renewables Certificate No. TC-GL-018A-2014, issued on December 9, 2014).
- GL – Energy Renewables Certification: Report Nr. 75138, Rev. 3, issued October 10, 2014, Compliance with the "Guideline for the Certification of Condition Monitoring Systems for Wind Turbines".

- GL – Energy Renewables Certification: Type Certificate BLADEcontrol. GL Renewables Certificate No. TC-GL-009A-2013, issued on October 8, 2013).
- Signal lines and connectors are conform to the lightning protection for wind turbines standard VDE 0127-24 (outline 06200) and lightning protection of electric and electronic systems in structural facilities, VDE 01854-4 (11-2002) (according to intern data sheet lightning protection). The case is conform to IP 66 according to EN 60529/10.91.

5.2.6 Track record of manufacturer, size of company, no. of installed systems

Bosch Rexroth AG is a large international corporation producing and supporting mechanical and plant engineering tools with over 33,700 employees world-wide. It is a subsidiary company of Robert Bosch GmbH which was founded more than 125 years ago.

The BLADEcontrol system was originally developed by the company IGUS Innovative Technische Systeme GmbH. Since 2009, IGUS-ITS GmbH has been majority-owned by Bosch Rexroth AG, became a wholly-owned subsidiary in 2011 and was renamed into Bosch Rexroth Monitoring Systems GmbH.

The BLADEcontrol ice detection system has been commercially available since 2006 and has reached over 2,500 machine years until 2015. The turbines monitored are located in Central Europe, Scandinavia and North America. The total number of systems sold is more than 1,400 (Table 4).

Table 4: Types of turbines with the Bosch Rexroth system installed.

Manufacturer	Turbine type
Vestas	V112/3000, V100 div MK, V90 div MK, V80-2MW, NM 82/1500, V72c/1500, V66
Senvion	5M, 3.XM (3.4M, 3.2M), MM92/2050, MM82, MM100
Nordex	N117, N100, N90
Areva	M5000-116, M5000-135
GE Energy	GE Energy 2.8-120, GE Energy 2.75-103, GE Energy 2.5-120, GE Energy 2.3, GE Energy 1.5 MW
Others	Acciona AW1500, Acciona AW116 3MW Enercon E-66, E-70, E-82, eno92, eno100, eno114, EWT DW54/900, EWT DW54/500 Fuhrländer FL MD/77, Fuhrländer FL 2500 Kenersys K82, K100, K110 Leitwind LTW77-1500 PowerWind 56 Siemens SWT-3.0-113 Suzlon S88 Schütz VT110

5.2.7 Available operational experiences

Currently, there are no independent evaluations of the BLADEcontrol system publicly available.

Bosch Rexroth has carried out an in-company evaluation. Presentations are available upon request. The following experiences have been shared:

- Accurate real-time operational data such as pitch angle, wind speed and power are required to generate a reliable signal.
- The system is more sensitive at the tip of a blade than at the root. It is thus difficult to provide information on ice mass. Ice thickness is considered a better parameter.
- Ice thickness is derived indirectly from frequency deviations assuming a "worst-case" distribution of ice on the blade, i.e. ice on the leading edge only, reaching to approximately 10 cm from the outer half of the blade.
- Turbine type calibration is possible by attaching defined additional masses (such as plumber lead strips) on the outer half of the leading edge, thus simulating the most common ice accretion which also has the highest possible mass concentration.
- There can be large differences in the timing of icing events between the turbines in the same wind farm.
- Several turbine manufacturers have performed their own studies which have not been made public yet.

5.2.8 Maintenance and durability

The BLADEcontrol system and all of its components are engineered to last over the lifetime of a wind turbine with a minimum of required maintenance work. After the installation of the BLADEcontrol system no visual inspection is needed.

5.2.9 References/Publications

- H. Wickman, Evaluation of field tests of different ice measurement methods for wind power, PhD theses, 2013
- D. Brenner, 2015 1,500 operational Years of Icing on Wind Turbines – A Long Term Study, Winterwind 2015.
- D. Brenner, 2015, BladeControl Workshop, "Detection of damage and ice: Monitoring"

- J. Reimers, 2015, Ice detection on wind turbines: Goals, methods, experience, International Conference “Anti-Icing for Wind Turbines”
- GL – Energy Renewables Certification: Type Certificate BLADEcontrol. GL Renewables Certificate No. TC-GL-018A-2014, issued on December 9, 2014).
- GL – Energy Renewables Certification: Certification of functionality, Report Nr. 75138, Rev. 3, issued October 10, 2014.
- IGUS (2005), “Ice detection systems for wind turbines, A review of the Ice and Rocks meeting in Oberzeiring, Austria on March 17/18th, 2005”
- BLADEcontrol® Greater output – less risk – Product Brochure, 2014
- BCA400-1000 Series ICP®-compatible High Sensitive Accelerometers Data Sheet, October 2010.
- BLADEcontrol_Referenzen_150121.pdf

5.3 eologix

5.3.1 Description of ice detection system/techniques

The eologix ice detection system is based on an impedance/capacitance sensing and further provides temperature monitoring (not necessary for ice detection). The variable impedance of multiple thin planar capacitors on the surface of the rotor blade is measured. The sensors are thin, flexible patches, installed with a patch of erosion protection tape at several locations on the rotor blade.

As a temperature measurement is carried out at the same time on the blade surface, the system can also be used for monitoring/control of a de-icing system.

5.3.2 Measured parameters, additional data required, calibration

The system measures rotor icing at specific spots on the rotor blade. It is capable of giving the following output signals:

- Free and dry surface
- Wet surface or very thin layer of ice (< ca. 1 mm)
- Ice thickness > ca. 1 mm
- Ice thickness > ca. 10 mm
- Further output signals for different thicknesses are feasible due to the underlying analogue measurement principle

Additionally, it measures the temperature of the blade surface.

The measurement range of the temperature sensor goes from -40 °C to +85 °C with a resolution of 0.25 °C. According to the manufacturer, the minimum thickness of ice that can be detected is less than 1 mm.

No additional operational data from the wind turbine is required to operate the eologix system. No calibration is needed on site.

5.3.3 Technical specifications, sensor position, power requirements

The eologix ice detection system consists of the following components (Figure 26):

- **Blade sensor CET214t:** wireless measurement devices on the surface of the rotor blade.
- **Base station BET214t:** data collection and processing, local data outputs (e.g. switch, Modbus, RS485 etc.) and transfer to the eologix server.

- **eologix server:** online monitoring system, basic data visualisation and data download function (Figure 27). This is an optional component and not necessary for operation.

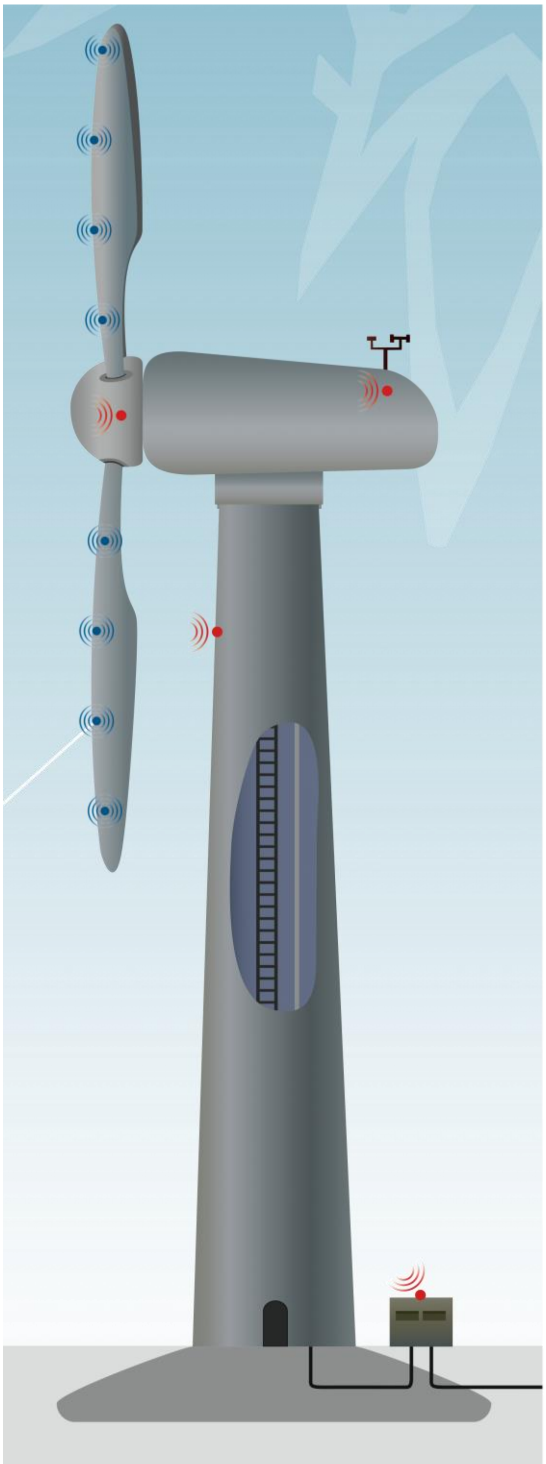

Figure 26: A sketch of a possible placement of the sensors (blue symbols). The red devices indicate possible locations of the receiving unit (only one position is required).

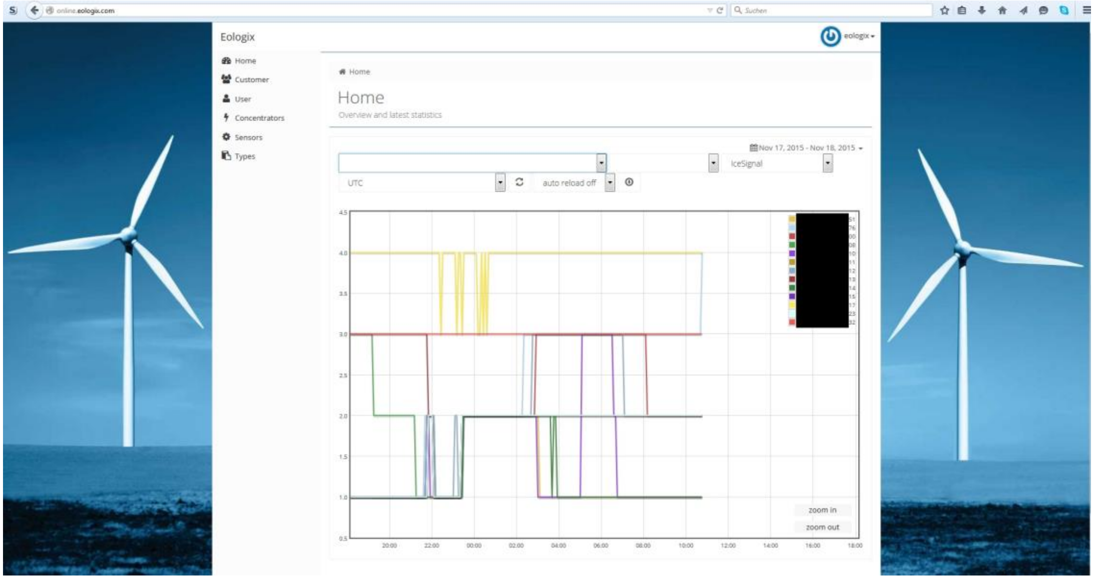

Figure 27: A screenshot of the online monitoring system.

The **blade sensor CET214t** is a wireless ice and temperature sensor. Due to its flexible design it can easily be attached to flat and curved surfaces such as rotor blades of wind turbines. It uses an SRD communication band and is powered from photovoltaic cells, thus offering unlimited time of operation without recharging or battery replacement. In order to bridge night time and longer periods of icing on the photovoltaic cells, energy storage elements are integrated in the sensor which allow dark time operation of more than 1,000 hours. The device is entirely sealed and does not require any electrical connections.

The CET214t sensor carries out two main tasks: acquiring measurement data and data computing on one hand side and wireless data transmission on the other. For icing detection, an impedance-type measurement circuitry is employed. For temperature measurement, an integrated circuit with a typical accuracy of 0.25 °C is used.

The dimensions of one sensor are 240 x 100 x < 2 mm (L x W x H). They are mounted to blades with erosion protection tape (pre-mounted on a sheet of 3M Wind Protection Tape W8607) which has dimensions of 360 x 254 x 0.3 mm. The weight of the sensor is 80 g including the tape. The operating temperature ranges between -30 °C and +60 °C, while operation at -40 °C has been successfully tested. The transmission frequency in the EU is typically 868 MHz (in a range between 863 and 870 MHz), and in North America 915 MHz (range: 902-928 MHz). The guaranteed communication distance is 250 m.

A minimum of 2 sensors per blade is required for ice detection by the certification body (DNVGL component certificate CC-GL-IV-1-00526-0), but 10 to 20 sensors per turbine are recommended by the manufacturer. There is no upper limit to the number of sensors per turbine. No sensor can be located further away than 5 cm from the leading edge in order to comply with the certified minimum configuration, while the user is free to place sensors wherever desired for other uses. There are no electrical wires in the blade so that lightning poses no danger.

The **base station BET214t** is the receiver for the CET214t blade sensor and compatible to ice and temperature sensors. Typical mounting positions for the device comprise of but are not limited to the nacelle and locations on ground near the tower of the turbine (e.g. in a substation or a transformer cabinet). The base station system consists of an electric cabinet and one or more receiver antennas with respective cabling, depending on the setup of the installation. These antennas receive signals transmitted by the CET214t and compatible sensors, store the data and transfer the data to the eologix online server for data processing and data allocation for the customer. Furthermore, switching signals are generated for turbine control (changeover relays: system OK/NOT OK and/or ICE/NO ICE).

Figure 28: eologix sensor mounted on the leading edge of the rotor blade.

The dimensions of the base station are 200 x 180 x 300 mm (L x W x H) with a weight of approximately 6 kg. The operating temperature ranges between -30 °C and +60 °C. The internal power supply requires 24 VDC (range: 12-28 VDC), and optionally 100 to 240 VAC is possible. The power requirement for the base station is typically 5W@24VDC.

The **eologix server** receives the data from the base station and stores it. Online access and local data interfaces are provided for the customer.

No access to real-time SCADA data is required by the eologix ice detection system. The measurement is independent of the operating mode, so ice detection is possible at standstill, while idling as well as during operation. No minimum wind speed is required for the detection.

The sensors can be retrofitted. The design of the sensors is suited for offshore use as well, but the sensors have only been applied onshore yet.

5.3.4 Output signal, data transfer, data format, software

The sensors exchange information with the receiving unit, called the base station, which can be located at the hub or the root of the blades, the met mast or on the ground or the tower. The sensors can be installed anywhere on the blade, or on outer surfaces of spinner, nacelle or tower. They deliver information exactly on those spots but not on the entire blade.

The system can also be connected to the SCADA system to interact with the turbine control for an automatic restart. A variety of optional interfaces are offered:

- Modbus TCP/RTU
- CANopen
- EtherCAT
- PowerLink
- Profibus
- Webserver (online database) for online data monitoring

Thresholds for ice detection cannot be modified by the user after delivery as the thresholds are determined by the certificate. However, for application outside certified scenarios, additional thresholds are offered and have already been implemented for customers.

5.3.5 Stage of development, technical maturity, available certifications

In 2011 the sensing principle was presented. Since then, various tests have been carried out, among them first field tests, a first icing wind tunnel test (2014) and a fatigue test on a car wheel trim. In 2014, eologix started a small scale production of the ice detection system after performing an initial leader lightning test on a blade according to ISO 61400-24, a fatigue test on a metal specimen at Graz University of Technology (12 million cycles @ 1000 ppm) and continuous tests in the FH Joanneum icing wind tunnel. In 2014/15, field tests on wind turbines were carried out. In winter 2015/2016, approximately 20 turbines will be equipped with the eologix system. The system has been commercially available since the beginning of 2014.

In 2015, the eologix sensor has been certified by DNV GL Renewables Certification (Component Certificate, Certificate No. CC-GL-IV-1-00526-0, issued on September 23, 2015).

eologix is collaborating with a number of turbine manufacturers to test the system.

5.3.6 Track record of manufacturer, size of company, no. of installed systems

eologix is a small start-up company originating from the Science Park in Graz, Austria with three founders. eologix aims at the industrialisation of smart sensors for particular fields of application such as renewable energies, robotics and sports. The company was founded in 2014 and rewarded an aws High-Technology pre-seed grant before founding.

The eologix ice detection system has been developed between 2011 and 2014 within the Science Park Graz and has become commercially available very recently. As per late 2015, the company has equipped approximately 20 turbines with their sensors (11 turbine types from 6 wind turbine manufacturers).

5.3.7 Available operational experiences

Currently, there are no independent field studies of the eologix ice detection system available. The system is tested on several wind turbines in Europe and Canada.

eologix has presented operational experiences from winter 2014/15 with Nordex N60 turbines in the UK, Bonus B52 turbines in Austria and Fuhrländer FL2500 turbines in Bulgaria. These analyses mainly focus on temperature measurements. At Winterwind 2016, eologix plans to present broad data analyses on icing distribution and icing scenarios.

5.3.8 Maintenance and durability

Regular maintenance includes optical inspection of the sensors on a routine base, e.g. once in two years.

By electrical and mechanical design, the expected lifetime exceeds 10 years. Erosion has to be considered, though. eologix advises using an additional erosion protection when small damages to erosion protection become visible.

5.3.9 References/Publications

- CET214t, Wireless Ice and Temperature Sensor for Rotor Blades, Preliminary Data Sheet, Rev. 2.1 05/2015
- BET214t Base Station for eologix Wireless Sensors Preliminary Data Sheet Rev. 1.1, 05/2015
- eologix product sell sheet

- M. Moser, T. Schlegl, H. Zangl, 2015, On the variability of temperature and icing status over the blades of wind turbines, Winterwind 2015
- M. Moser, T. Schlegl, H. Zangl, 2014, Retrofittable, autonomous and wireless icing and temperature monitoring on rotor blades for efficient anti- and de-icing, Winterwind 2014
- Winterwind 2011, 2012 and 2013, SAE 2015

5.4 fos4Ice Detection (fos4X)

5.4.1 Description of ice detection system/techniques

Dynamic fibre-optic acceleration transducers are installed in the turbine blades to measure the natural frequency of the elastic rotor blades. The acceleration due to vibration of the blades is altered in case of icing by the mass increase. After recording the sensor signals, a frequency analysis is performed to determine the relevant frequency components. The change in vibration frequency is proportional to the added mass to the blade. This method thus provides an ice signal as well as the estimated ice mass.

5.4.2 Measured parameters, additional data required, calibration

The system is able to detect meteorological icing (ice growth on the blades) and rotor icing (ice presence on the blades). It is also able to determine whether the blade is free of ice. The fos4IceDetection system is able detect icing at standstill, while idling and during operation. The only requirement is that the wind speed exceeds 3 m/s. Because ice detection is based on vibration measurements, the method monitors icing on the whole blade.

During the frequency analysis, which determines the added mass on blades, real-time SCADA data (wind speed, pitch angle, rotor speed and temperature) should be included to increase resolution and to decrease uncertainties of the signal processing. Ice detection is also possible without this data but it increases uncertainty and is not recommended in practice. Figure 29 shows a schematic drawing of the signal flow.

The sensors are best installed as close to the tip as possible. A mounting position at about one third of the blade radius is generally chosen when retrofitting the system. The manufacturer recommends installing one sensor on each blade but any number of sensors can be used. These sensors measure individually and a blade-specific alarm is given if any of the sensors detects ice.

The lower limit for detection of ice loads is < 10 kg per blade. The ice detection system is most sensitive within the last third towards the tip of the blade.

A calibration procedure has to be carried out during the commissioning of the fos4IceDetection system. The calibration procedure is performed automatically on the wind turbine during normal operation. Typically, such a calibration takes about two to four weeks to ensure a significant amount of operational states under various environmental conditions. It is also possible to transfer calibration data between different turbines of the same type to shorten the calibration procedure to a few hours. After calibration, user-defined ice mass thresholds can be set to define warning and alarm levels.

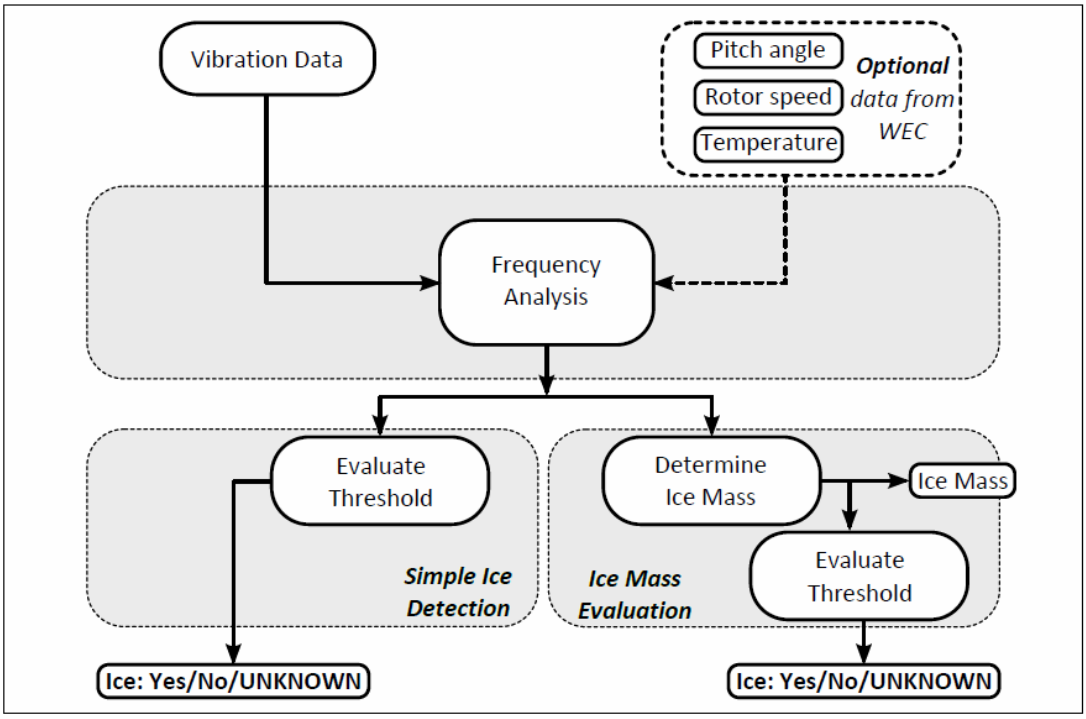

Figure 29: Schematic drawing of the fos4IceDetection system's signal flow for one blade.

5.4.3 Technical specifications, sensor position, power requirements

The fos4IceDetection system mainly consists of the **fos4Acc 2D sensor** inside the rotor blade and the **fos4Blade Hub Control Cabinet** (Figure 30). The industry PC housed in the fos4Blade Hub Control Cabinet runs the fos4IceDetection software.

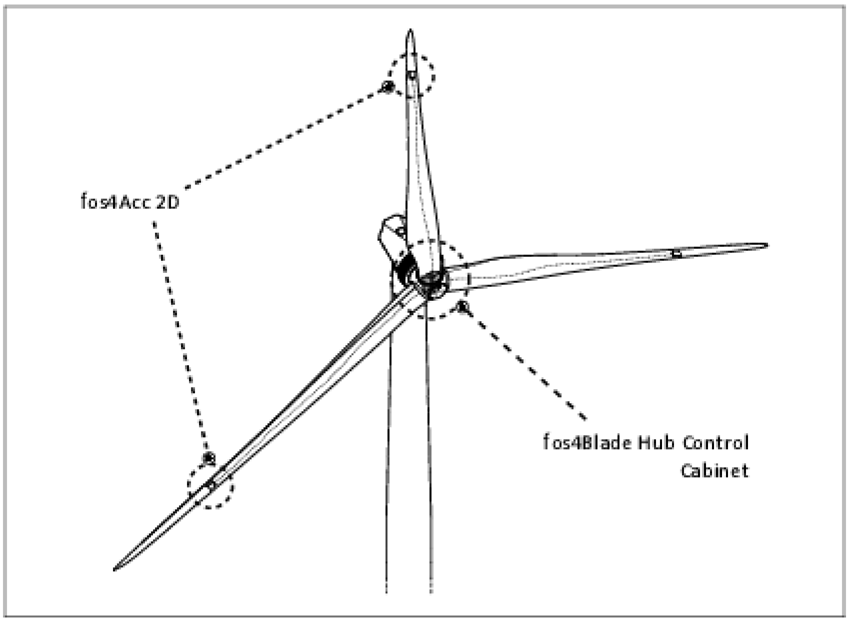

Figure 30: Schematic drawing of a wind turbine equipped with a fos4IceDetection system for every blade (not true to scale) with the two main components, the fibre optic 2D acceleration sensor fos4Acc 2D and the fos4BladeHub Control Cabinet.

The **fos4Acc 2D sensor** (Figure 31) is designed to measure accelerations of structures in two dimensions and was developed to be applied inside the blades of a wind turbine. A fibre bragg grating is used as a sensing element in the optical fibre. The accelerometer is sensitive in two dimensions and can be screw mounted or glued to the vibrating structure. The optical working principle makes the sensor immune to electromagnetic interference and lightning. No electric power or electrical wires are required in the blade.

The fos4Acc 2D sensors can either be retrofitted or installed during manufacturing of the blades. They are designed to last for the entire lifetime of the turbine and to be maintenance-free. The dimensions of the sensor are 55 x 80 x 124 mm (H x W x L) and the weight is 500 g.

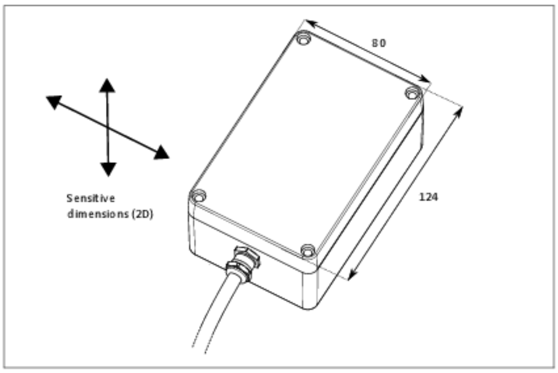

Figure 31: Schematic drawing of a fos4Acc 2D sensor.

The **fos4BladeHub Control Cabinet** is made of stainless steel, providing IP65 protection. The cabinet can either be powered with 230 V @ 50 Hz or 24 V DC and has a maximum power consumption of less than 150 W. Internally, two fuse protected circuits separately power the heating unit (< 70 W) and the measurement unit and data processing unit (< 80 W) of the fos4Blade wind measurement unit. Every electrical signal and supply path is backed with an individual lightning protection module. The dimensions are 480 x 350 x 208 mm with a weight of 30 kg.

The connectors on the cabinet are designed to be resistant against shocks and vibrations. The fos4Blade Hub Control Cabinet is certified according to DIN EN 60068-2-6 Class 3M6 and DIN EN 60068-27 Class 3M. The system is suitable for onshore as well as offshore wind turbines.

5.4.4 Output signal, data transfer, data format, software

Several different interfaces are available to connect the fos4IceDetection system to the wind turbine.

As one possible customer interface, the fos4IceDetection system uses the IEC 61400-25 standard (developed for monitoring wind power plants) to provide information to the turbine. IEC 61400-25 defines several communication service mappings to provide the underlying communication protocol. The fos4IceDetection system uses the IEC 61850-8-1 (MMS) communication mapping.

Alternative interfaces currently available include communication via CAN bus or Modbus TCP. Further interfaces can be developed on request. If no communication bus is available, the communication with the wind turbine can also be realised using low-power digital outputs (ice alarm, ice warning, and system operational) and analogue inputs (wind speed, rotor speed, pitch angle, temperature).

For simple monitoring and maintenance tasks the fos4IceDetection system provides a webserver interface allowing a supervision of the main functionalities and states, and a configuration of settings and thresholds.

The system can easily be complemented with fibre optic strain sensors for blade load measurement at the blade roots. This enables active load reduction schemes and extended condition monitoring functionality.

5.4.5 Stage of development, technical maturity, available certifications

The first prototype was installed in the year 2011. Since 2013, the system is being produced on small scale and being tested with different turbine manufacturers. In autumn 2014, the fos4IceDetection system was certified by DNV GL. A large field test has been carried out in winter 2014/15 together with Senvion SE and a second large manufacturer.

Currently, the system is being retrofitted on roughly 40 Senvion SE turbines. A smaller number of systems are being tested by four other major turbine manufacturers.

The following certifications of the fos4IceDetection system are available:

- DNV GL – Energy Renewables Certification: Type Certificate fos4IceDetection. GL Renewables Certificate No. TC-GL-013A-2014, issued on September 15, 2014.
- DNV GL – Energy Renewables Certification: Certification Report for the Ice Detection System “fos4IceDetection”, GL Renewables Report No. 75159-16, issued on September 15, 2014.
- DNV GL – Energy Renewables Certification: Certification of functionality, Report Nr. 75286, issued July 2, 2015.
- CE requirements as well as to DIN EN 60068-2-6 Class 3M6 and DIN EN 60068-27.
- ISO 9001:2008 certificate, issued by TÜV SÜD on December 6, 2012.

5.4.6 Track record of manufacturer, size of company, no. of installed systems

The company fos4X is a spin-off of the technical university of Munich. It was established in 2010. Today, fos4X has 30 employees. Fos4X is specialised in the development of fibre-optic products for different industries. The fos4IceDetection is one of the systems produced by fos4X.

Up to now, 16 fos4Ice Detection systems have been installed in Germany, Austria, Canada and the Czech Republic. By the end of the winter 2015/2016 about 50-70 fos4IceDetection systems will have been installed.

5.4.7 Available operational experiences

There are no reports publicly available but an extensive field test was carried out in the winter 2014/2015. Results from this field test can be made available upon request.

5.4.8 Maintenance and durability

The fos4IceDetection system and all its components are engineered to last over the lifetime of a wind turbine with a minimum of required maintenance.

After the installation of the system fos4X recommends an annual visual inspection within the first three consecutive years of operation. After that, a maintenance interval of three years is sufficient.

5.4.9 References/Publications

- fos4Ice detection sell sheet.
- fos4IceDetection Product Manual, July 14, 2015
- fos4Blade Hub Control Cabinet Product Manual, July 15, 2015
- fos4IceDetection data sheet, V0.8 – PRELIMINARY
- fos4Acc Vibration measurement sensor Data sheet, February 27, 2015
- DNV GL – Energy Renewables Certification: Type Certificate fos4IceDetection. GL Renewables Certificate No. TC-GL-013A-2014, issued on September 15, 2014.
- DNV GL – Energy Renewables Certification: Certification Report for the Ice Detection System “fos4IceDetection”, GL Renewables Report No. 75159-16, issued on September 15, 2014.
- DNV GL – Energy Renewables Certification: Report Nr. 75286, issued July 2, 2015, Compliance with the "Guideline for the Certification of Condition Monitoring Systems for Wind Turbines"
- Müller, Schmid - Feldtestdaten eines Eiserkennungssystems auf Basis von faseroptischen Sensoren, 6. VDI-Fachtagung "Schwingungen von Windenergieanlagen 2015", ISBN 978-3-18-092242-3, June 3, 2015.

5.5 Wölfel IDD.Blade

5.5.1 Description of ice detection system/techniques

The IDD.Blade ice detection system is an option of the SHM.Blade condition monitoring system by Wölfel. IDD.Blade measures vibrations of turbine blades with structural noise sensors based on acceleration and temperature measurement developed by Wölfel and specifically designed for ice and structural damage detection on turbine blades. Changes in blade mass due to icing cause deviations from the normal in vibration eigenfrequency and in the dynamic response. Based on a calibration, a threshold can be defined and exceedances can be identified as ice.

5.5.2 Measured parameters, additional data, calibration

The IDD.Blade ice detection system detects rotor icing. The system provides an indicator that is proportional to the ice mass and can be correlated to the thickness of the ice on the blade in mm. Because the detection is based on blade vibrations, the method delivers information on the conditions on the whole blade. The area with the highest sensitivity is close to the tip of the blade. The system provides an ice warning signal and an icing alarm signal as condition indicators. Figure 32 shows a flow chart of the ice detection algorithm.

For a blade in the range of 60 m in size, the recommended detection thresholds correspond to an ice thickness of 3 mm (change in eigenfrequency: -0.75%) for the ice warning signal and of 6 mm (change in eigenfrequency: -1.5%) for the ice alarm signal. If necessary, the detection of ice can be increased to a higher sensitivity. When the Eigen frequencies return to normal range, a "no ice" signal is given.

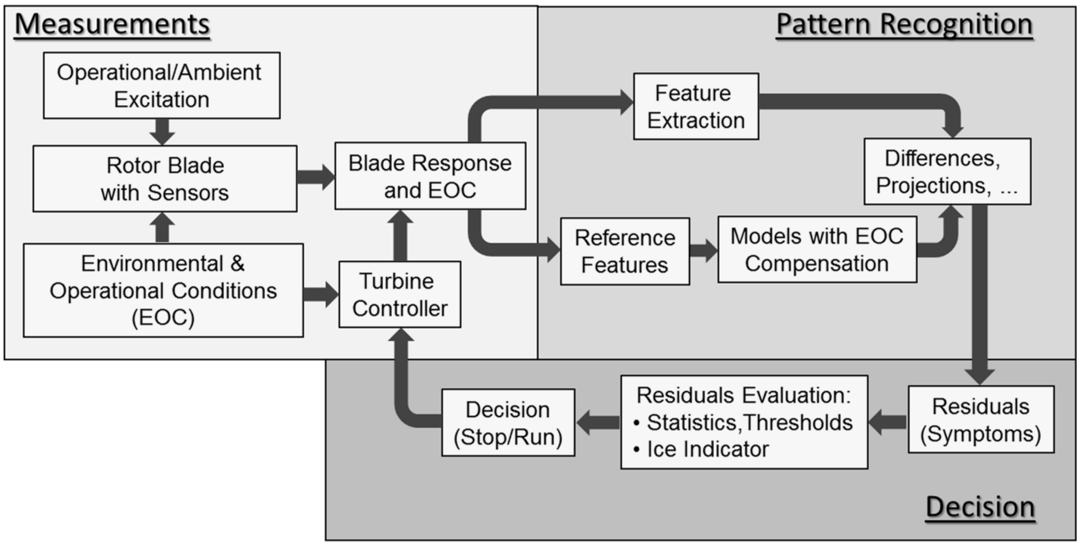

Figure 32: Flow chart of the algorithm behind IDD.Blade.

IDD.Blade detects ice at standstill, while idling and during operation. A minimum wind speed of 2-3 m/s is required for ice detection.

The IDD.Blade ice detection system requires real-time access to operational data of wind speed, power, rotor speed and pitch angle with a resolution of 1 Hz to assess the dynamic properties of the blade accurately and to detect deviations from the normal.

After commissioning of the system, a calibration period of approximately two to four weeks is performed to identify suitable thresholds for ice warning and alarm. The exact length of the calibration period depends on the environmental and operational conditions. The calibration performs automatically. Once a new turbine type has been calibrated, the parameters gained can be used to calibrate other turbines of the same type.

The thresholds for ice detection can be modified by the manufacturer but not by the operator by default. The thresholds will be set during the commissioning of the system and can be adopted site-specifically to fulfil various requirements of approval. For example, less populated areas often allow more relaxed thresholds than industrial or residential areas.

5.5.3 Technical specifications, sensor position, additional data required, power requirements

The IDD.Blade ice detection system consists of the following components (Figure 33):

- **Structural Noise Sensors** (SNS) in each rotor blade
- **Data Acquisition Unit** (DAU) in the hub
- **Connection boxes** at the roots of the blades in the accessible area
- **Data Processing Unit** (DPU) in the nacelle

One or more sensors can be installed per blade. While one sensor is the standard configuration, more sensors will increase redundancy and accuracy as well. A cold climate version of the system exists for sites with particularly low temperatures.

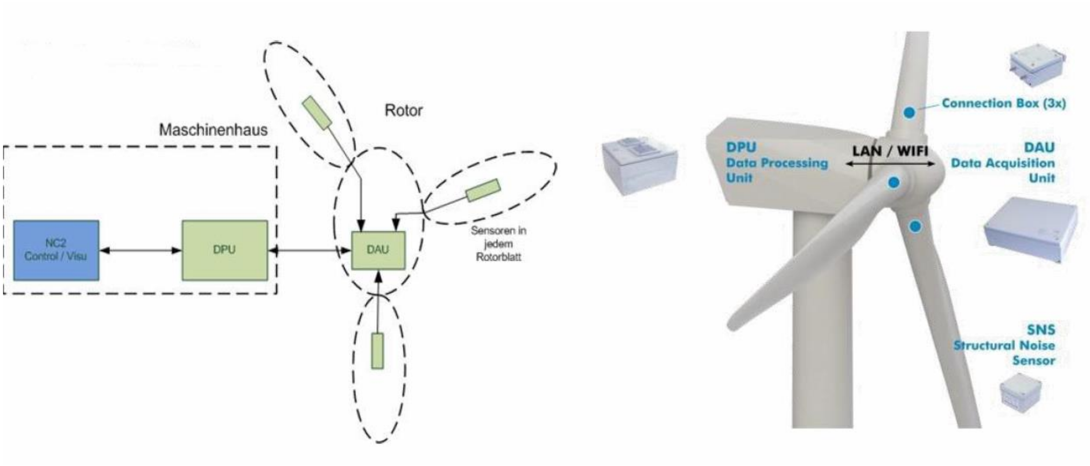

Figure 33: A schematic illustration of the IDD.Blade components on a wind turbine. DPU = Data Processing Unit, DAU = Data Acquisition Unit, SNS = structural noise sensor

The **SNS sensors** are installed by screwing them onto a mounting plate which is then glued onto the blade in advance. The manufacturer recommends installing the IDD.Blade sensor at a standard distance of 12 to 18 m from the blade root, depending on the type of rotor blade. This can be optimised with the manufacturer depending on the turbine type. All components are lightning protected. The dimensions of the SNS sensors are 126 x 127 x 91 mm and they weigh 1.5 kg each.

The SNS sensors are positioned in the accessible area of the rotor blade near the root. Electronic components are optimised with regard to the installation space and power consumption required.

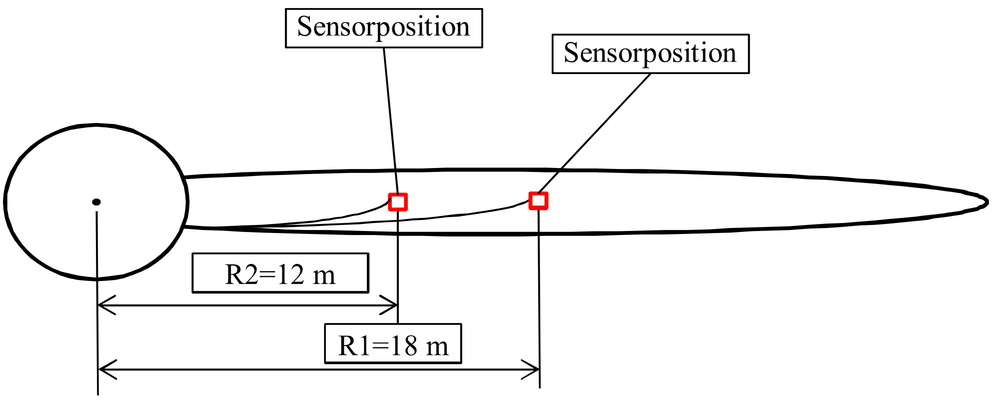

Figure 34: Recommended position (R1) of the IDD.Blade sensors on the blade. R2 is the recommended position of an optional second SNS sensor in the blade.

The **data acquisition unit (DAU)** in the hub serves for power supply of the SNS sensors, overvoltage protection and for digitizing and pre-processing the analogue sensor signals (4-20 mA). The sensors are connected with the DAU via the connection box in the root of each blade. The DAU has dimensions of 400 x 300 x 120 mm and a weight of ca. 13 kg. Each connection box has a dimension of 126 x 127 x 91 and a weight of ca. 1.5 kg. The internal power supply requires 24 VDC. The power requirement for DAU including sensors is 230V at approximately 40W. The system runs internally @24V.

In the **data processing unit DPU**, the measured data are processed fully automatically and the condition indicators for damage and icing (with the option IDD.Blade) are calculated. At the same time, the communication with the turbine control and the data connection to external monitoring centers are realised from the DPU.

The dimensions of the DPU are 380 x 380 x 210 mm and it weighs ca. 13 kg. The internal power supply requires 24 VDC. The power requirement for DAU including sensors is 230 V at approximately 40 W. The system runs internally at 24V.

The operating temperature ranges from -20 to +50°C (standard version) or from -40 °C to +50°C (cold climate version).

The system can either be retrofitted or installed during manufacture. The assembly time for retrofitting is approximately 1-1.5 days with 2 persons. The configuration and commissioning can be made via web interface.

The system can be designed for offshore applications.

5.5.4 Output signal, data transfer, data format, software

The IDD.Blade ice detection system provides an icing warning signal and an icing alarm signal. The complete system can be operated remotely via a standard browser/web interface.

The communication between the DAU and the DPU is established through ftp/LAN, optionally WLAN.

The turbine control is established by the DPU. Currently the following interfaces for interaction with the wind turbine are supported:

- Modbus/TCP and OPC according to IEC 61400-25
- FTP (file-based data transfer)
- Analogue signals (current and voltage signals)

Also other customer specific interfaces can be provided by Wölfel.

5.5.5 Stage of development, technical maturity, available certifications

The prototype installation of the ice detection system IDD.Blade took place in 2011/12. The serial production of all components started and the product was released on the market in 2012/13.

The IDD.Blade ice detection system has been developed and tested exclusively with Nordex until the end of 2015. The SHM.Blade system is already running on different turbines such as Enercon (E-82 and E-101) and also on Vestas and DeWind turbines.

The exclusivity of Nordex will be released by the end of 2015 and the IDD.Blade ice detection feature will become available for all turbine suppliers in 2016.

Available certifications of the system are:

- GL – Energy Renewables Certification: Type Certificate SHM.Blade / IDD.Blade. GL Renewables Certificate No. TC-GL-015A-2013, issued on September 5, 2014.
- GL – Energy Renewables Certification: Certification report, Report Nr. 74981-16, Rev. 1, issued September 5, 2014. "Compliance with the "Guideline for the Certification of Condition Monitoring Systems for Wind Turbines".
- Assessment by TÜV NORD "Begutachtung eines schwingungsbasierten Eiserkennungssystems auf Basis von Mehrkörpersimulationen", VDI-Berichte 2242, 2015.
- Signal lines and connectors are conform to the lightning protection for wind turbines standard VDE 0127-24 (outline 06200) and lightning protection of electric and electronic systems in structural facilities, VDE 01854-4 (11-2002) (according to intern data sheet lightning protection). The case is conform to IP 66 according to EN 60529/10.91.
- Electromagnetic compatibility (EMC) according to IEC 61000-6-2.

Some further new features for the system such as the detection of aerodynamic imbalance and pitch angle misalignment are in the pipeline and are planned to be released on the market by 2016.

5.5.6 Track record of manufacturer, size of company, no. of installed systems

Wölfel Group is a vibration specialist, which produces services, systems and software for monitoring based on vibration analysis for various industries. The company was founded in 1971. The Wölfel Group currently employs over 90 people and is active in Europe as well as intercontinentally. The Wölfel Group consists of three companies:

- Wölfel Beratende Ingenieure: Engineering service in the field of mechanics, dynamics and acoustics.
- Wölfel Messsysteme: Developing and distributing high-level software- and hardware-products in the field of vibrations, noise and immission control.
- Wölfel Wind Systems: Services and products related to wind energy.

In the field of wind energy, Wölfel Wind Systems offers the following products:

- RoBin, a measuring system for acoustic noise emission of wind turbines
- IDD.Blade / SHM.Blade for ice detection and condition monitoring of rotor blades
- BD.5 and BD.10, vibration exciters for modal analysis and structural testing
- FCMS, foundation and tower monitoring systems for offshore structures
- ADD.Sound, active absorbers for tonality control of geared and non-geared wind turbines

The company is accredited according to the following standards:

- Certification after DIN EN ISO 9001:2008 for the following scope: Consulting, Analysis and Design, Measurement, Development and Manufacturing of Systems in Strength of Materials, Dynamics, Acoustics for Mechanical, Civil and Plant Engineering.
- Accreditation according to DIN EN ISO/IEC 17025:2005 for testing in the fields: Determination of noise and vibrations, noise measurements at wind turbines, noise and vibrations at workplaces, aircraft noise, building acoustics, module immission control.
- In Bavaria and other federal states Wölfel has been officially acknowledged as measuring institution according to § 29b BImSchG for the determination of emissions and immissions caused by noise and vibrations.

Up to now, around 100 IDD/SHM.Blade systems have been installed in wind turbines. Until now, the system has been serially installed on Nordex turbines (N100, N117, N131).

The SHM.Blade system is already running on different turbines such as Enercon (E-82 and E-101) and also on Vestas and DeWind turbines. The IDD.Blade Ice detection feature will be released and available for all turbine suppliers in 2016.

5.5.7 Available operational experiences

A comparison study of the system (and other ice detection systems) was carried out by the Nordex Energy GmbH in Sweden in the winter season 2011/12.

In Germany, a field study was performed in a wind farm in Hessen by Nordex in 2014/15.

5.5.8 Maintenance and durability

The manufacturer recommends maintaining the overvoltage protection in the DAU and the DPU annually. Also the attachment of the sensors should be checked preferably once a year.

5.5.9 References/Publications (also those sent by the manufacturers)

- B. Wölfel, 2015, Reliable ice detection for rotor blades to increase availability and yield, International Conference “Anti-Icing for Wind Turbines”.
- GL – Energy Renewables Certification: Type Certificate SHM.Blade / IDD.Blade. GL Renewables Certificate No. TC-GL-015A-2013, issued on September 5, 2014.
- GL – Energy Renewables Certification: Certification report, Report Nr. 74981-16, Rev. 1, issued September 5, 2014. Compliance with the "Guideline for the Certification of Condition Monitoring Systems for Wind Turbines".
- “TÜV-NORD; M. Bülk, H. Gülzau, F. Lautenschlager” Begutachtung eines schwingungsbasierten Eiserkennungssystems auf Basis von Mehrkörpersumulation. VDI Fachtagung „Schwingungen von Windenergieanlagen 2015“ VDI Bericht 2242; ISBN 978-3-18-092242-3
- Wölfel SHM.Blade / IDD.Blade product brochure, 2013.
- Installation and Maintenance Manual SHM.Blade, September 29, 2104.
- Parametrization of thresholds for ice detection, October 25, 2013.
- Manual for commissioning SHM.Blade, October 24, 2014.
- Product Specification SHM.Blade / IDD.Blade, Juni 12, 2013.
- P. Kraemer, H. Friedmann and Ebert, C., 2015: Vibration-based Ice Detection of Rotor Blades in Wind Turbines—The Industrial Realization of an SHM-System, 10th International Workshop on Structural Health Monitoring, Stanford University, USA, S. 2841-2848.

- Ebert, C., Kraemer, P. and A. Löwe, 2013. Zuverlässige Eiserkennung an Rotorblättern, VDI-Berichte 2200, 4. VDI-Fachtagung Windenergieanlagen, Bremen, Germany, pp. 215-221.

6 Systems not manufactured anymore

6.1 HAICMON$_{ice}$/Hainzl

The HAICMON$_{ice}$ detector (Figure 35) developed by Hainzl Industriesysteme monitors Radio Frequency Electromagnetic Fields (RFID) and detects ice at frequency changes. It was part of the Hainzl Condition Monitoring system. RFID is the wireless, non-contact application of radio-frequency electromagnetic fields to transfer data, to automatically identify, track and sense the condition of transponders attached to objects.

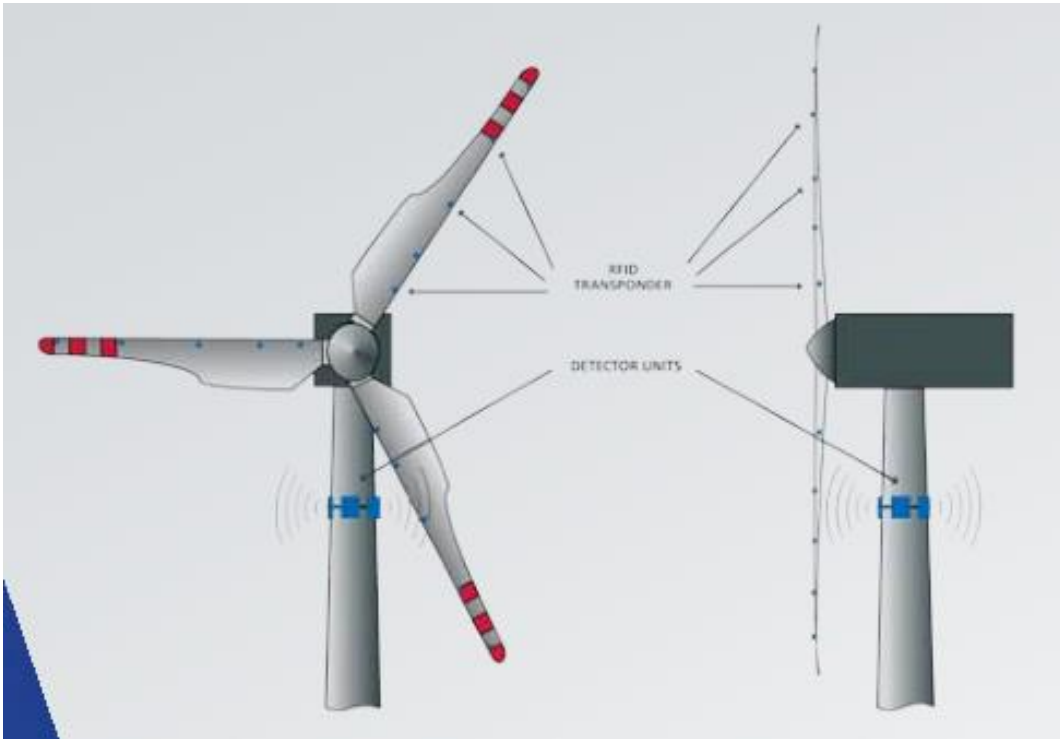

Figure 35: A sketch of the function principle of the HAICMON$_{ice}$ detection system.

It can detect instrumental icing and can deliver an "ice" and a "no ice" signal (analogue I/O: OK/NOK, ICE YES/NO). It detects ice only on specific spots on turbine blades where the sensors are installed. It can detect ice during operation and idling, but not at standstill. It does not require SCADA data to function but can be connected to the SCADA system for an automatic restart of the turbine.

The system is mounted by a clamping ring on the tower or by fitting into holes in the tower. The cable routing can be installed either inside or outside of the tower, depending on holes available on the tower. The cables are fixed by strong magnets and tension belts.

The RFID transponders are mounted onto the critical areas of the rotor blades. Up to 15 transponders per blade are recommended, depending on the size of the blade. The transponders are self-adhesive and have a thickness of < 0.5 mm. An erosion protection foil is provided against environmental conditions. The operating temperature ranges between -30 °C and 50 °C. The $HAICMON_{ice}$ detector can be retrofitted or installed during manufacture.

The power supply is 120/230 VAC at 50/60 Hz. The power consumption is maximally 190 W. A CAT5 for SCADA connection and a shielded cable for supply and GPIO are provided. The connection between SCADA and $HAICMON_{ice}$ is by IEC61400-25, Modbus TCP.

The technical maturity of the system was at a prototype stage and more R&D would be required. No certifications are available.

6.2 Infralytic

The Infralytic ice sensor (Figure 36) is a fiber optic cable which points out of the blade near the tip. The signal is transferred to the sender/receiver, located in the hub, via optical fibers. From there the signal is sent to the control unit and can be used as warning for icing. The principle of the measurement is an infrared signal produced by LEDs (Light Emitting Diodes). The signal is sent through the cable to the tip, where it is partially reflected, and in the case of icing, characteristically absorbed. Based on the absorption, the system calculates an ice thickness. Because of a varying scattering of signals due to different types of ice only a mean thickness can be determined.

The sensors are installed into the blades near the tip. Every sensor unit can be equipped with up to three fibers, enabling measurement on every blade. The sensor tip is 2 mm in diameter. Data transfer to the control unit is wireless. A measurement is possible every few seconds, allowing for a rapid detection of ice. The system is designed to be free of maintenance.

Laboratory tests performed with 50 m sensor fibers show a successful detection of ice. The fibre tips were tested for possible false alarms due to dirt and were found to weaken the signal but be distinguishable from ice.

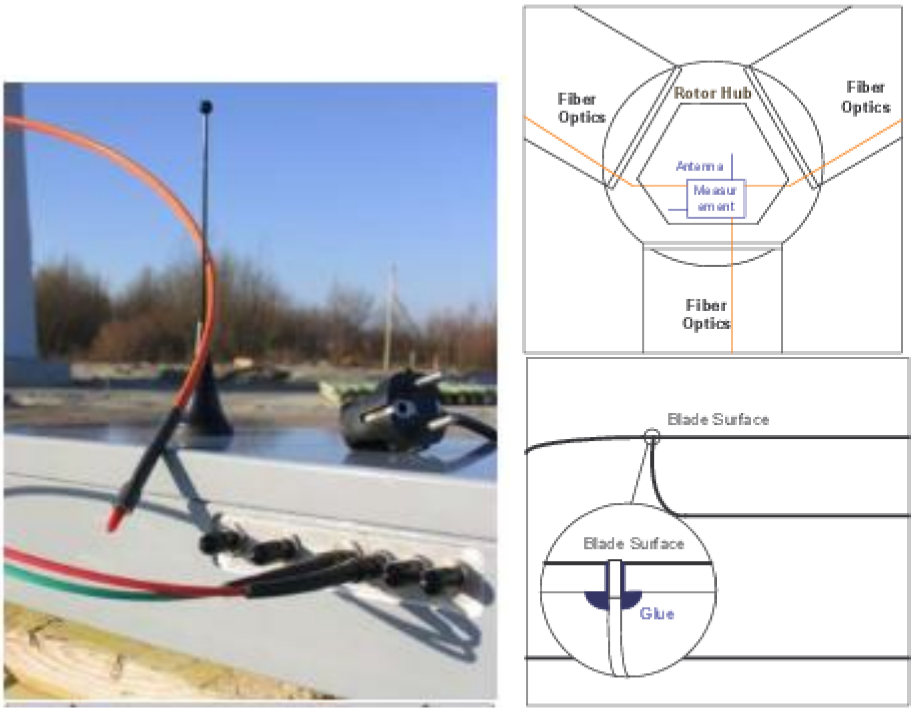

Figure 36: The sensor tip with sender/receiver (left); sketch of a rotor hub (top right) and a possible sensor location in the blade (bottom right)

6.3 MOOG/Insensys

The MOOG/Insensys method (Figure 37) performs load measurements using fibre optics technology. Four strain measurement patches are installed per blade, near the root of the blades. They measure the strain, the mass and the center of mass of each blade in real time. The system was originally developed for monitoring the pitch angle of the blades but the sensors can be used to monitor the mass increase of the blades due to ice. The parameters delivered are the estimated ice mass and the mass growth rate. The system can detect ice during operation, idling and at standstill. At standstill a minimal wind speed is necessary. A calibration procedure is required, which runs automatically at the commissioning of the system.

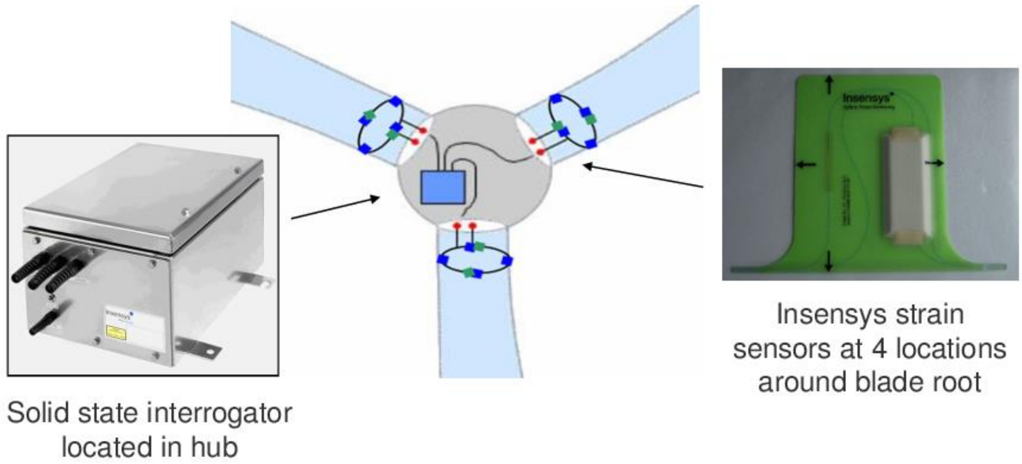

Figure 37: A sketch of the function principle and the location of the sensors of the MOOG/Insensys ice detecting system.

The system provides an "ice" as well as a "no ice" signal based on predefined, adjustable thresholds for ice mass (for example 80 kg during 7 minutes, equivalent to approx. 4 mm of ice on leading edge). The minimum ice mass detected is 20 kg on a 6000 kg blade. It can be connected to the turbine control system to perform an automatic restart if "no ice" is detected. The system is independent of SCADA data. Data transfer occurs via GSM/GPRS. The system is designed to be free of maintenance.

The sensor patches are mounted by glue. They are immune to lightning and can be either retrofitted or installed during manufacture.

The control unit can either be installed into the hub or the cabinet. It is supplied by 24 VDC and their typical power consumption is 3 W. The operating temperature ranges between -40 °C and 65 °C.

The system was tested in the field at St. Brais in Switzerland in 2009 with an Enercon E-82 wind turbine. The system performed well and reached a data availability of 100%. Another field study was carried out in Germany with a Vestas V80 turbine. The system performed well and allowed for reducing the hours of shutdown compared with a nacelle-based ice detection system.

The system is also used to monitor and control blade imbalance and yaw misalignment.

7 Comparison nacelle based systems

Figure 38 shows an overview on nacelle based systems and types of icing which they measure. It is obvious that none of these systems is able to measure rotor icing, which is crucial for efficient and safe operation of wind turbine under icing conditions.

Figure 39 compares the year of commercialisation, the number of sold systems and the stage of development of the nacelle based systems. Figure 40 summarizes the certifications available, independent field studies and the main findings from operational experiences.

Temperature and relative humidity provide none of the icing parameters. The Goodrich 0871LH1 model and the Labkotec LID-3300IP have the highest number of systems in use and are the only systems with certifications available. Several independent field studies exist. They show that all systems have their shortcomings under different conditions. Labkotec and Goodrich have the highest technical maturity.

		Principle	Meteorological Icing	Instrumental Icing	Rotor Icing
NACELLE BASED SYSTEMS	Temperature & relative humidity	Temperature < xx°C Relative Humidity > xx%	No (potential)	No	No
	Heated versus unheated anemometer	Significant deviation between heated and unheated anemometer	No	Yes	No
	Leine Linde Systems IPMS	Temperature < xx°C Relative Humidity > xx% Video livestream	No (potential)	Yes (camera)	Yes (camera)
	Combitech Ice Monitor	Vertical freely rotating cylinder Load Cell	Yes	Yes	No
	Goodrich 0871LH1	Ultrasonic vibrating finger Decrease of amplitude during icing	Yes	No*	No
	HoloOptics T40 series	Reduced infrared reflection when probe covered with ice	Yes	No*	No
	Labkotec LID-3300IP	Ultrasonic vibrating wire Decrease of amplitude during icing	Yes	No*	No
	Sommer IDS-10	Change of impedance on surface when probe covered with ice	Yes	No*	No
	PMS Meteorological Monitoring System	Vertical non- rotating cylinder Load Cell	Yes	Yes	No
	New Avionics Ice Meister 9734	Change of opacity and index-of-fraction when probe iced	No	Yes	No

Figure 38: Overview on nacelle based systems and types of icing which they measure (*instrumental icing can be measured if heating is deactivated. In that case, meteorological icing cannot be measured anymore.)

		Commercially available since	No. of systems (on turbines) sold	Stage of development
NACELLE BASED SYSTEMS	Temperature & relative humidity	long time	n/a	Serial
	Heated versus unheated anemometer	long time	n/a	Serial
	Leine Linde Systems IPMS	2010	40 (40)	Small scale series
	Combitech Ice Monitor	2005	50 (20)	Single pieces on demand
	Goodrich 0871LH1	1994	250 in 2014	Serial
	HoloOptics T40 series	2009	40 (20)	Small scale series
	Labkotec LID-3300IP	2002	3000	Serial
	Sommer IDS-10	2016	0	0-series
	PMS Meteorological Monitoring System	1998	80 (0)	Small scale series
	New Avionics Ice Meister 9734	2014	n/a	Serial

Figure 39: Year of commercialisation, number of systems sold and stage of development of the nacelle based systems.

		Certification	Independent field studies	Operational Experiences
NACELLE BASED SYSTEMS	Temperature & relative humidity	n/a	Yes	strong overestimation, excessive false alarms
	Heated versus unheated anemometer	n/a	Yes	Principle OK, robust, heated anemo gets iced too
	Leine Linde Systems IPMS	In process	No	n/a
	Combitech Ice Monitor	designed according to ISO 12494	Yes	Principle OK, not robust, drift, noisy signal, heating too weak
	Goodrich 0871LH1	cTUVus (USA)	Yes	Principle OK, robust, Igloo, partly false alarms
	HoloOptics T40 series	No	Yes	Principle OK, not robust, heating too weak, partly false alarms
	Labkotec LID-3300IP	GL Component Certificate UL/CSA certificate VTT icing wind-tunnel	Yes	Principle OK, robust, heating too weak, partly false alarms, individual settings important
	Sommer IDS-10	No	No	n/a
	PMS Meteorological Monitoring System	No	Yes	Principle OK, robust, stable signal
	New Avionics Ice Meister 9734	n/a	No	n/a

Figure 40: Comparison of the certifications available, independent field studies and the main findings from operational experiences.

8 Comparison blade based systems

Figure 41 shows an overview on blade based systems and the types of icing which they measure. It is obvious that all systems are able to measure rotor icing, which is crucial for efficient and safe operation of wind turbine under icing conditions.

Figure 42 summarizes the main characteristics regarding ice detection, operational modes and additional data required. The power curve method is not able to detect icing during stand still. All systems except the eologix system require a minimum wind speed of 2 m/s or higher. The eologix system is the only one which does not require access to real-time operational data and which measures icing only at specific spots.

Figure 43 compares the number of sensors required, typical sensor positions and type of installation, the presence of electrical wires in the blade and the possibility for retrofit. The power curve method as well as the fos4IceDetecion and the eologix systems do not have any electrical wires in the blade.

Figure 44 compares the year of commercialisation, the number of systems sold and the stage of development of the blade based systems. The power curve method is applied very frequently. The BladeControl system has the highest number of systems in use. The other systems have a significantly lower number of systems in use. This is explained by the fact that fos4IceDetection, Wölfel IDD.Blade and eologix are very new systems compared to the BladeControl system.

Figure 45 summarizes the available certifications, independent field studies and the main findings from operational experiences for the blade based systems. All systems are certified. No independent field studies exist for any of the blade based systems. A first benchmark between the BladeControl, eologix and fos4IceDetection systems is being carried out in Gaspé, Canada during winter 2015/16.

		Principle	Meteorological Icing	Instrumental Icing	Rotor Icing
BLADE BASED SYSTEMS	Power curve	Deviation between produced power and power curve at low temperatures	No	No	Yes
	fos4 Ice Detection	Fibre-optic Accelerators Change in Eigenfrequency when blade is iced	Yes	No	Yes
	Bosch Rexroth BladeControl	Piezo-Electric Accelerators Change in natural oscillation frequencies when blade is iced	Yes	No	Yes
	Wölfel SHM.Blade/ IDD.Blade	Structural Noise Sensors (accelerators), change in Eigenfrequency when blade is iced	Yes	No	Yes
	Eologix	Change of impedance/capacitance on sensor surface when probe iced	No	No	Yes

Figure 41: Overview on blade based systems and types of icing which they measure.

		Operation	Standstill	Minimum wind speed	SCADA data required	Anywhere on blade
BLADE BASED SYSTEMS	Power curve	Yes	No	3 m/s	Yes	Yes
	fos4 Ice Detection	Yes	Yes	3 m/s	Yes	Yes
	Bosch Rexroth BladeControl	Yes	Yes	2 m/s	Yes	Yes
	Wölfel SHM.Blade/ IDD.Blade	Yes	Yes	2-3 m/s	Yes	Yes
	Eologix	Yes	Yes	0 m/s	No	No

Figure 42: Overview on blade based systems and their main characteristics regarding ice detection, operational modes and additional data required.

		No. of sensors	Sensor position	Electrical wires in blade	Blade sensor Installation	Retrofit
BLADE BASED SYSTEMS	Power curve	none	n/a	No	n/a	n/a
	fos4 Ice Detection	Minimum 1 per blade	1/3 of the blade radius	No	inside glued	Yes
	Bosch Rexroth BladeControl	Minimum 1 per blade	1/3 of the blade radius	Yes	inside glued	Yes
	Wölfel SHM.Blade/ IDD.Blade	Minimum 1 per blade	12- 18 m from root	Yes	inside glued	Yes
	Eologix	Minimum 2 per blade every 10 m recommended	leading edge	No	outside taped	Yes

Figure 43: Overview on number of sensors required, typical sensor positions and type of installation, the presence of electrical wires in the blade and the possibility for retrofit of the blade based systems.

		Commercially available since	No. of systems sold	Stage of development
BLADE BASED SYSTEMS	Power curve	n/a	Enercon: > 1690 turbines	serial
	fos4 Ice Detection	2013	50-70 by end of winter 2015/16 (~40 x Senvion)	Small scale series all turbine types
	Bosch Rexroth BladeControl	2005	> 1500 (300 in 2015)	Serial all turbine types
	Wölfel SHM.Blade/ IDD.Blade	2012	100 (Nordex)	Serial for Nordex Available for all turbine types in 2016
	Eologix	2015	~20	Small scale series all turbine types

Figure 44: Comparison of the year of commercialisation, the number of systems sold and the stage of development of the blade based systems.

		Certifications	Independent field studies	Field tests
BLADE BASED SYSTEMS	Power curve	n/a	(Yes)	
	fos4 Ice Detection	GL Type Certificate GL Condition Monitoring	No	2014/2015 results available on request
	Bosch Rexroth BladeControl	GL Type Certificate GL Condition Monitoring	No	own evaluations
	Wölfel SHM.Blade/ IDD.Blade	GL Type Certificate GL Condition Monitoring	No	Nordex Sweden 2011/12 Nordex Germany 2014/15
	Eologix	GL Component Certificate	No	Winter 2015/16 results at Winterwind 2016

Figure 45: Comparison the certifications available, independent field studies and field tests carried out by the manufacturers.

9 Overview on ice protection systems

Ice protection systems either remove ice from the rotor blades or prevent ice build-up on the blades. The following technical approaches exist:

- **Hot air heating**: Hot air is blown into the rotor blades in order to remove the ice. This approach has a high technical maturity.
- **Electro-thermal heating**: Electro-thermal heating elements are mounted internally (factory installed) or externally (retrofit) on the leading edge of the blade. The technical maturity of factory installed electro-thermal heating systems is moderate to high, while it is low for retrofit solutions.
- **Microwave:** A coating on the blade surface which can be heated with microwave generators inside the blade. The technical maturity is low.
- **Coatings**: Dedicated ice-phobic coatings to prevent ice accretion. The technical maturity is low.

The decision for a de-icing system has to be taken before the construction of a wind park. Once a wind turbine is installed, only few options for improvement are available. A list of available ice protection systems is given in Table 5. A more detailed overview can be found in the IEA Task 19 Available Technologies report[8].

Table 5: Available ice protection systems

OEM	Type of ice protection system
Acciona	Hot air
Adios	Electro-thermal (third party)
Alstom	Hot air
Dongfang	Hot air and electro-thermal
Enercon	Hot air
GreenWindGLobal (ECOTemp)	Electro-thermal (third party)
Gamesa	Hot-air/electro-thermal/coating
Kelly-Aerospace	Electro-thermal (third party)
Nordex	Electro-thermal
Senvion	Hot air
Siemens	Electro-thermal
Vestas	Hot air
WiceTec (VTT)	Electro-thermal (third party)

8 IEA Wind Task 19, 2016, Available Technologies for Wind Energy Projects in Cold Climate, edition 2016, publication expected mid 2016.

10 Overview on icing forecasts

10.1 Introduction

Wind power forecasts have become well-established in power industry today. Forecasts of the next days' energy production are used for network management, energy trade and maintenance planning. Icing events can bias power forecasts. Affected by icing, a wind park might not be able to deliver the predicted power and requires compensation, which again affects network stability. Accurate icing forecasts would greatly improve the integration of wind energy to energy market. However, the development of ice forecast models is still in its infancy.

10.2 Components of an icing forecast system

Icing forecast models in use today typically consist of three components:

1. A **numerical weather prediction model** (NWP) creates meteorological parameters required for assessing the possibility of icing.

2. An **ice accretion model** calculates the ice accretion given the meteorological conditions delivered by the NWP.

3. A **production loss model** converts the wind speed and wind direction predicted by the NWP as well as the calculated ice accretion to a production loss for a wind park.

The three components of the modelling system are described in the following. The scientific maturity of these model components decreases in the order of description. The weather prediction models are used on a daily basis in nearly all countries in the world and evaluated and developed by a vast number of institutions. Their quality is very high in comparison. In case of ice accretion models, the community predicting icing on wind turbines is very small and there is virtually only one 1D model currently applied for time-dependent icing forecast. The production loss models, in turn, suffer from being of economic interest. Turbine manufacturers are rarely willing to share their models or data, which hinders the development of the models.

10.2.1 Numerical weather prediction model (NWP)

An accurate icing forecast builds on accurate meteorological input data. These are obtained from a mesoscale numerical climate model simulation. A fairly large number of such models exist world-wide. Those well-established in Europe include:

- WRF (Weather Research and Forecasting model, http://www.wrf-model.org).

- ALADIN (Aire Limitée Adaptation Dynamique Développement International, http://www.cnrm.meteo.fr/aladin/)
- AROME (Applications of Research to Operations at MEsoscale, http://www.cnrm.meteo.fr/arome/),
- HIRLAM (HIgh Resolution Limited Area Model, http://www.hirlam.org),
- COSMO (COnsortium for Small-scale MOdeling, http://www.cosmo-model.org)

The driving meteorological parameters for build-up of ice are cloud liquid water content (LWC), droplet size distribution, temperature and wind speed. An accurate simulation of these parameters requires a detailed parameterisation of cloud microphysics on a high spatial and temporal resolution. Achieving this high grade of detail still remains a challenge due to two main reasons: Firstly, understanding cloud processes and correctly parameterising them requires complex measurements of cloud parameters under various meteorological conditions. The technology to perform such measurements is, to a large extent, not available. Secondly, computing power allowing for high resolution simulations has not been available. The recent development of new, dual-polarised Doppler radar device to measure cloud parameters and the increasing computing resources in the beginning of the century have enabled increasingly accurate simulations with mesoscale regional NWP models on a kilometre scale.

First tests employing the WRF model were carried out within the COST Action 727 (Measuring and forecasting atmospheric icing on structures) between 2007 and 2009. The results were highly encouraging. The methodology to calculate icing, as described in this chapter, was first used within research projects to plan overhead power lines and later to create icing maps. Such maps exist today for Finland (www.tuuliatlas.fi), Norway and Sweden (www.vindteknikk.no) and Switzerland (www.wind-data.ch). Publicly available for free, WRF is the most often used mesoscale model for icing forecasts today. Further models in use include COSMO and AROME.

Central for an accurate icing forecast is a careful choice of the cloud microphysics scheme in the NWP, and the best possible use of the boundary condition data (data assimilation) as well as the horizontal and vertical resolution. This has been found in various sensitivity studies (Oechslin, 2009; Nygaard, 2011; Davis, 2013). So far the Thompson scheme (Thompson et al., 2004) for cloud microphysics in WRF has been found to be most successful. However, new and improved parameterisations become available with every new release of the WRF model. NCAR (National Center for Atmospheric Research, USA), the developer of the WRF model, employs the model for their weather forecast and is thus constantly developing and testing new parameterisations. But also other models offer detailed parameterisations for cloud processes. Horizontal resolutions in use today are typically 1-3 km, depending on the size of the area of interest, and the complexity of the terrain. It has been shown that in flat terrain a high-quality icing forecast can be obtained with a modest resolution as well (roughly 10 km, Oechslin, 2009).

Validation of NWP model results in terms of wind speed and temperature is straight forward. The parameters relevant for ice accretion, cloud water and droplet number concentration remain difficult to evaluate, as so far no instrument can measure these parameters during icing conditions. This complication is twofold: first, no icing data from weather stations is available to validate the icing conditions predicted by the model, and second, little information on the actual ice build-up is available from wind turbines to evaluate the ice load predicted by the ice accretion model.

10.2.2 Ice accretion model

The existing ice accretion models calculate the temporal evolution of ice accretion on a structure in one location based on meteorological parameters from a NWP model. The most commonly employed ice accretion model simulates icing on a vertical cylinder (Makkonen et al., 2001). This 1D method was originally developed to calculate icing on overhead power lines to estimate the expected ice load during planning. The drawback of this model is that the cylinder is steady. The model thus can't accurately represent the form of a turbine blade, or the wind speeds experienced by a rotating blade. Furthermore, the parameterisation of ice ablation (melting, sublimation and mechanical effects) is rudimentary. Experiences show that while the start of icing events is fairly well simulated, the model underestimates the ablation processes. The predicted icing periods are too long, leading to over-accumulation of ice.

Two- and three-dimensional ice accretion models also exist, such as LEWICE, TURBICE and FESAP. They are capable of simulating ice accretion on a rotor blade correctly, but the computational power required is too high for the models to be used operationally. Furthermore, these models cannot deal with time series but use stationary meteorological conditions.

Newer one-dimensional approaches, such as the "iceblade" model (Davis, 2014a) are currently under development. They intent to give a realistic representation of ice accretion on a rotor blade, taking the form and the wind speed into account. These models still require further research.

10.2.3 Production loss model

Production loss models are the weakest link in the icing forecast chain. Only a limited number of models exist and their validation is not sufficient. On the one hand, the modelling of icing on a rotor blade is uncertain due to the lack of sophisticated models. On the other hand, only very few observations of ice accretion on rotor blades and the resulting loss of production are available from wind park operators. After all, the losses strongly depend on the operation mode of a turbine, the ice detection method used and the potential heating of rotor blades. Turbine manufacturers provide little or no information on these issues.

The strategy to establish a production loss model is thus to apply statistical methods and neural networks, which create a statistical relationship between icing and production loss during a training period based on SCADA data, other observations from the wind park and a first attempt to model production losses. The improved relationship will then be used for further prediction of production losses (Karlsson, 2014; Söderberg, 2015). Another approach builds on a three-dimensional, empirical power curve which describes the production as a function of not only wind speed but also ice load and the duration of an icing event.

10.3 Summary and outlook

Icing forecasts for wind parks are still a new field of study. The scientific maturity of the models is low. The time-critical nature of the icing forecasts poses another challenge. The forecast has to be available by a given time for the turbine operator to react accordingly. This can be difficult in terms of the high computing resources required for an accurate forecast.

Operational icing forecasts have become topical only during the last few years. The demand has commenced and created research activity, especially in Scandinavia. The recent project Icewind (Improved forecast of wind, waves and icing, http://www.icewind.dtu.dk) was dedicated for investigating possibilities in icing forecast. In central Europe only one developer is known to be engaged in icing forecasts (Dierer and Cattin, 2010; Dierer et al., 2013).

So far only deterministic forecasts have been made. Only one ensemble type forecast of one NWP has been investigated in a research project by the Swedish meteorological office SMHI using their ensemble system HarmonEPS (Persson Söderman, 2015). Ensemble type forecasts are beneficial because they assess the uncertainty in terms of a likely spread of the predicted variables. A sophisticated use of this information can reduce uncertainty of a deterministic forecast. A number of providers of icing forecasts (Kjeller Vindtekknik, DNV GL, Meteotest, WeatherTech and more) exist today. The focus is clearly in Scandinavia. Assessments of uncertainty are very vague and base on rudimentary statistical quantities, such as bias or RMSE. No standards exist for evaluation of icing forecasts. A very first independent benchmark has been realised and presented in 2016. Merely one study has been published that compares different production loss models using identical input data (Davis, 2014b). The study shows that the models results compare reasonably well, but there is still great room for further development.

Very recently, positive results with liquid water content of precipitation measured by a Micro Rain Radar MRR compared with model results from WRF have been obtained on a test site in Canada. This indicates first steps towards the possibility for a validations of liquid cloud water amounts and microphysics schemes for icing forecasts.

10.4 References

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