Technical Requirements for Rotor Blades Operating in Cold Climate

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1. Introduction

Wind turbines are increasingly erected at inland sites with their cold climate conditions as the coastal areas are already used for wind energy and offshore projects not yet entered the realisation phase. Furthermore, today's serial produced turbines easily reach lower clouds at winter time even close to the sea coasts. How future large offshore plants will be affected by icing events is not clear at the moment, as the necessary information and meteorological measurements at various offshore sites are not yet available. Inland sites and especially sites in mountainous and northern regions as well as large turbines will be affected by ice during standstill and operation [1]. The first large wind farms such as the Tauernwindfarm in Austria have been commissioned and first operation results are now available [3, 2]. Prototypes of wind turbines up to the Megawatt scale have been equipped with blade heating systems with special sensors and other features in order to fit the turbines to cold climate sites. However, no standard cold climate serial produced wind turbines are available on today's market. This paper summarises and discusses technical solutions and gives guidance on the systems which can be used for the various cold climate conditions.

2. Cold Climate Site Effects on the Design of a Wind Turbine

Cold climate sites will affect the design of a wind turbine in different ways: Ice and rime as well as high air density at low temperatures will cause severe effects on the aerodynamics and thus, on the loads and the power output of the turbine. Temperature effects and especially high masses of ice on the structure can change the natural frequencies of wind turbine components and change the dynamic behaviour of the whole turbine. Also, the control system can be affected. The stall of the rotor may occur earlier or later due to changed airfoil shape, the electrical or hydraulic pitch control can change their settings. Frozen or iced control instruments give faulty information to the supervisory system of the turbine. Extreme low temperatures will require special materials. For example normal steel will become brittle at those temperatures. The safety of the wind turbine as well as the vicinity at the site will be also affected by icing or in general by cold climate operation. Ice fragments thrown away or even large ice pieces falling down from the rotor can harm persons or animals or damage objects. The structural integrity of the turbine itself can be affected by heavy unbalance due to unsymmetrical icing and by resonances caused by changed natural frequencies of components exceeding the design fatigue loads. Low air density can increase the loads and maximum power output. If the turbine does not automatically react, windings or transformers may burn, gearboxes can be overloaded and damaged. Also the overall economy of wind energy projects will be affected by cold climate operation, especially at ice endangered sites. The site prognosis has to include type and duration of icing events and the frequency distribution of the temperature has to be known in correlation to the wind situation in order to predict the energy production as well as down times due to icing. Possibly, a special class of cold climate turbine has to be defined, as the standard IEC classes 1 to 4 will not apply at those sites. This may require special equipment of the turbines such as heating elements for the blades, heating of gear boxes and electronic boards, use of special steel for extreme low temperatures, heated wind vanes and anemometers or special ice sensors. Special requirements for maintenance and repair at cold climate sites should be taken into account even during the planning phase and the calculation of the economics of the project. The access to the site may be impossible if the roads are iced or full of snow for longer periods. In these conditions the erection, maintenance or repair of the turbine will not be possible or will produce long standstill periods without power production. Measurements with heated anemometers might to be erroneous and measurements with unheated sensors could underpredict extreme wind speeds which may occur in the high mountains mostly in combination with icing events as been seen in the measurements at the Tauernwindfarm [3]. In the ice map for Europe [1] areas have been catalogued according to the number of icing days such as no icing, rare icing and frequent icing. However, this can only be a first step for a more precise assessment of cold climate identification. Even the national or regional legislation could affect a wind farm project as building permission can require certain distances to roads and objects for safety reasons due to ice throw.

3. Definition of Cold Climate Sites

How can icing at a specific site be detected? The standard weather observation by the meteorological services in Europedoes not deliver all information to enable a reliable prediction of icing events in quality and quantity as documented in [1] mostly. Additionally, to the wind, air pressure, air temperature, and humidity, which are the standard quantities to be observed at the weather stations, the height of the clouds and the liquid water content should be known. As this is not be done at the stations, other indicators have to be found to get an idea about icing event at the prognosis sites. One of the possibilities to detect ice is the observation of already installed wind turbines, power lines, trees or high antenna towers in the neighbourhood of the planned site. Ice fragments found on the ground close to wind turbines as shown in Fig. 1 after icing events, reports from utilities about frequent damages of power lines due to icing, forestry experts reporting of damages due to rime ice will be useful indicators for the quality and frequency of icing events. Reason for these icing events can be undercooled fog occuring during wind speeds suitable for energy production. Also, low clouds will cause so-called in-cloud icing at large wind turbines, the top rotor position of which can easily reach the clouds where the undercooled water will cause ice accretion at the leading edge. During the operation a properly installed digital camera proved to be a quite reliable instrumentation to detect icing events as shown in [3]. However, ice detection by observation needs manned campaigns and is thus extremely expensive, especially a continuous observation also at night. Ice sensors seem to be a solution for an automatic and reliable ice detection. This can be performed either by special ice sensors directly or by recording of standard instruments indirectly. For the first choice commercially available instruments can be used and first tests are reported in [1]. Recent measurements at the Tauernwindpark compared with parallel observations and measurements of heated and unheated anemometers created some doubts about the trustworthiness of the sensors [2]. First long term measurements with two types of anemometers - a heated and an unheated one - at the Tauernwindpark showed ambiguous results during icing events or snow fall at very low temperatures as described in [4] and shown in Fig. 2. The example shows a measurement of the wind speed at hub height at the Tauernwindpark by using a cup-heated and a non-heated anemometer. The meteorological situation could be identified by recording the temperature and pictures from the site with a webcam (time series in 20 minute intervals). The left picture shows an icing event where the heated anemometer shows higher wind speeds than the unheated, which is expected. On the next day the temperature dropped to several degrees below zero and heavy snow fall started, combined with wind speeds up to 15 m/s. On the heated anemometer the snow melts on the hot cups and the water is transported by centrifugal forces to the outer part of the cups. The "forced convection" caused by the low temperature and the high wind speed let the melted snow immediately "re-freeze" on the outer radius. The resulting higher inertia and drag causes lower rotational speed of the anemometer and therefore faulty wind speed indication. On the other hand, the unheated anemometer remains cold. The snow hitting the cups does not melt and is reflected at the cups' surface and thrown off by the centrifugal forces. Thus, no big effect on the wind speed measurement is recognised which is seen in the right side of Fig. 2 where the unheated anemometer shows much higher wind speed compared to the heated one. In the middle of the Figure can be seen that without icing or precipitation the two anemometers record the same wind speed. Consequently, ice detection by using a heated and a non-heated anemometer should be used cautiously as an indicator for icing events. Another detection of even small amounts of ice accretion can be the increase of aerodynamic noise from the rotor blades. In [5] a measurement during the

Fig. 1 Typical ice indicators: From the left, iced power lines, lightning conductor, grass on the ground, rime ice fragment from a rotor blade found on the ground.

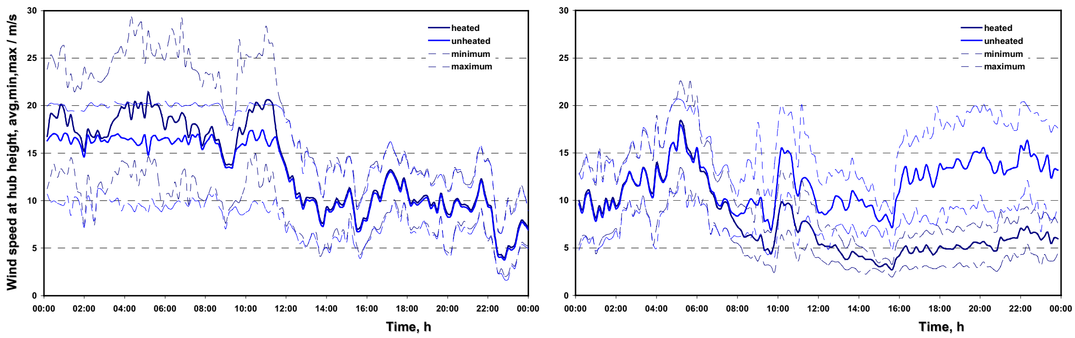


Fig. 2 Example for a two days wind speed measurement at Tauernwind. 10 - minute averages, minima and maxima of the heated and non-heated hub height anemometers.

beginning of slight icing at the leading edge and the resulting increase of noise as well as the shift of the frequency to higher levels. The disturbed aerodynamics result in fully turbulent boundary layer from the leading edge on and thus produces a higher noise and frequency level which can be heard clearly. Ice detection by detection of damages such as break down of meteorological masts or power lines due to buckling and possibly resonances of the structures caused by the high additional masses should be an exception, but can be an additional indicator at sites, where heavy icing is not expected.

Fig. 3 Typically iced rotor blades, here examples at MW turbines. The leading edge contour is marked by the white line.

4. Strategies

Various strategies of operating a wind turbine at ice endangered sites can be selected. The first parameter is the expected duration of icing. It is obvious that at sites where icing events are unlikely, no strategy is necessary. At sites where ice events will occur rarely, such as some days in a year, it is recommended to detect the icing events either by using ice free anemometers and vanes combined with temperature measurements and power curve observation, or to install one ice sensor per farm. During the icing events the turbine can either operate, idle or be stopped, depending on the situation at the site (close to roads or objects). It has to be defined under which circumstances the turbine may restart after icing events, automatically or only after a visual inspection. At sites with a high probability of icing - e.g. several weeks per year - an active or passive de - icing or anti - icing system for the rotor blades is recommended. At many sites in northern Europe the wind speeds during the icing season are relatively high so that long down times due to iced rotor blades will cause high losses of production.

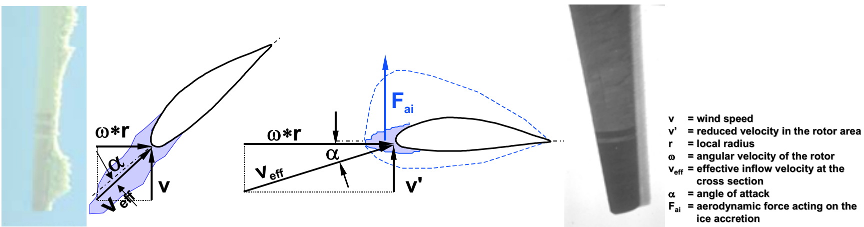


Fig. 4 Icing at leading edge at different modes of operation. Left side idling, right side power production.

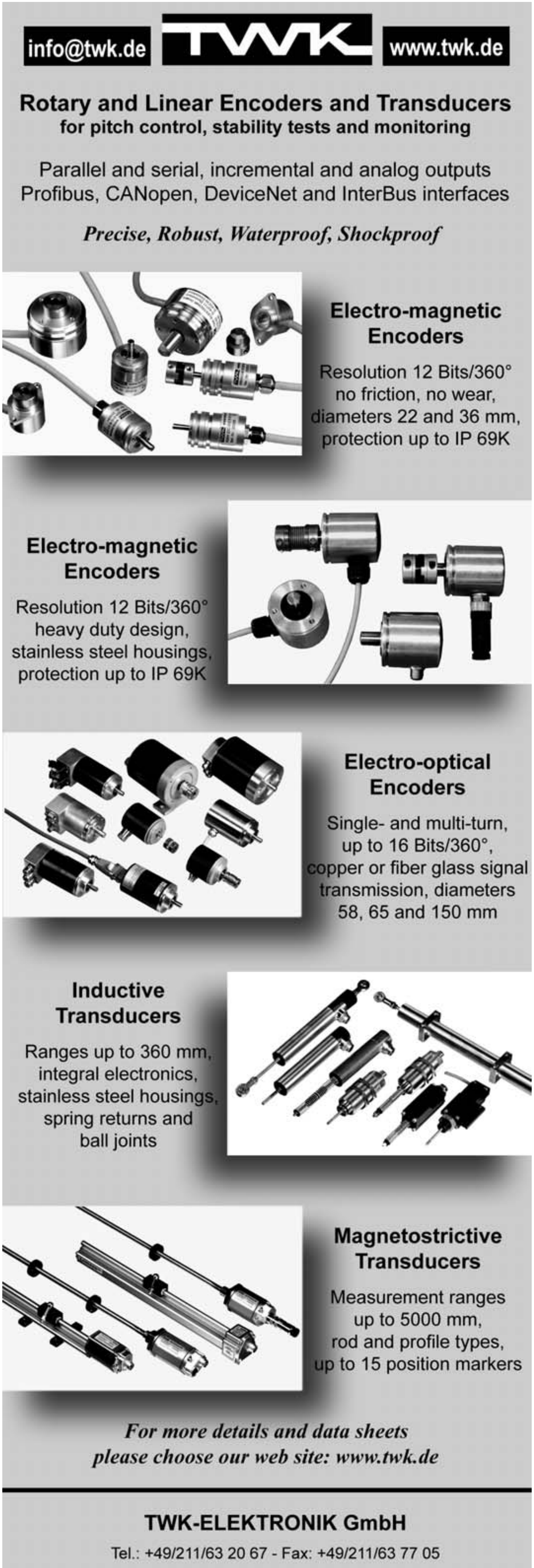
5. Types of Rotor Blade Icing

During the rotation of the rotor blades in icing weather conditions the leading edge of the rotor blade collects more and more ice around the stagnation point of the airfoils. Due to the increasing air velocity along the radius, the ice accretion builds up more at the outer part of the blade with an approximately linear increase which is depicted in Fig. 3. In principle, two types of icing during operation can occur, clear ice and rime ice. The right sketch in Fig. 4 shows the situation of a cross section of a rotor blade during operation with ice accretion at the leading edge. The cross section area increases as the "chord length" of the airfoil grows. Aerodynamic forces act on the ice fragment and - if too large - breaks it off. New ice builts up and the leading edge will look like a saw blade after some time. The left side of the Fig. 4 shows the situation at low wind speed when the turbine is idling. Here the aerodynamic forces on the ice fragment are very small and no centrifugal forces will act on it as the rotor speed is close to zero. The shear forces between the ice and the blade's surface are small and the ice can build up to a large amount at the leading edge as shown in the left side of the Figure where the ice piled up during idling. In [5] also events are presented where the three rotor blades of the same pitch controlled turbine during operation show different ice accretion. The ice at the leading edge has been thrown off close to the tip unsymmetrically resulting in an aerodynamic and mass imbalance.

6. Removing Ice from the Rotor Blade

Two types of systems to prevent wings from icing are known in the field of aviation. **De-icing** systems and **anti-icing** systems, where the first one actively removes the ice from the wing and the second one prevents the wing from icing. Also in the wind energy these two concepts have been tested at prototypes and small serial production lines. As anti-icing systems so-called **passive systems** are used for example in painting the rotor blades black. The advantage is that at daylight the blade heats up and the ice melts earlier than with white painted blades. However, in summertime the temperature of the blade's surface may affect the material properties of the glassfibre reinforced plastics (GRP), which is sensitive to high temperatures. Also special coatings which shall reduce the shear forces between the ice and the blade's surface are put to test at one of the Tauernwind turbines. Tests of different coatings have been performed in the Kanagawa climatic wind tunnel and reported at the BOREAS 6 conference [6]. The advantages of coating the whole surface of a rotor blade are relatively low costs, no special lightning protection is required, the blades are easy to maintain and the whole surface is protected. Furthermore, these types of coating may reduce the sensitiveness against dirt and bugs during the warm periods, improving the aerodynamic performance of the rotor. Disadvantages are the ice throw during operation. It is expected that the ice fragments will break off regularly and will be thrown away from the rotor. At heavy icing conditions and low wind speeds due to low shear forces during idling, there will be also large ice accretion at the leading edge. Also unsymmetrical ice accretion can be possible, leading to unbalance. Fig. 4 demonstrates the situation at a pitch controlled turbine during idling (left side) and operation (right side). It is assumed that in case of a small ice accretion at the leading edge the shear forces are relatively small and thus the ice will break off only if the aerodynamic and centrifugal forces on the fragment are strong enough. There are also two principles to be discussed for the active systems: A **de-icing system**, which removes collected ice during operation or idling and an **anti-icing system** which avoids the accretion of ice on the rotor blades during operation or idling. Small airplanes often use **mechanical de-icing** systems by means of so called inflatable rubber boots on the leading edge of the wing and control surfaces [5]. However, for wind turbine rotor blades with their high centrifugal loads at the outer radii a pneumatic system will inflate itself or has to be divided in short sections. Furthermore, it will disturb the aerodynamics and cause more noise. During the 20 years of service life of a wind turbine under harsh climatical conditions the rubber boots will require intensive maintenance which may not be economical.

In the past, active heating of the blade or parts of it have been tested or are under operation. Typical technical solutions are electrically heated foils at the leading edge (heating wires or carbon fibres) or blowing warm air into the rotor blade at standstill. Heating the rotor blade interior with warm air needs special tubes to pipe the hot air. The advantages are that the leading edge surface and thus the blade's aerodynamics is not affected. There is also no negative effect on the lightning protection system. At standstill the complete surface can be de-iced. On the other hand, GRP material is a good insulator. During high wind speeds or during rotation of the rotor at low temperatures the forced convection will require very high heating power. If this heating system is used at standstill at low wind speeds after icing events the high energy prices without production have to be paid by the operator. During operation - for pitch controlled turbines also at idling and standstill - it is sufficient to heat the area around the stagnation point of the airfoil only. In practice, heating elements at the blade's leading edge are mounted. The use of heat-



ing foils at the blade's leading edge surface has proved to be an effective anti-icing method during operation as reported in [1]. Also the heating power balance recommends this type of anti-icing system as experienced in Northern Finland [1]. Without any heating systems at these types of sites, the turbine would be full of ice over a long period, just at the time when the good winds are blowing. Heating foils can be applied at most of the rotor blades even after manufacturing them. However, the blade' s surface at the leading edge, where the air flow is most sensitive, is disturbed. Depending on the attachment of the foils, the aerodynamic performance of the airfoil might change during the un-iced conditions. With stall and active stall controlled turbines at standstill, e.g. during icing conditions combined with low wind speeds, the trailing edge might head towards the wind and thus collect the ice. Leading edge heating elements will not help de-icing this blade as Fig. 5 demonstrates. The right side shows the rotor blade of a stall controlled turbine yawed out of the wind during a period of in-cloud icing on the top of a mountain in southern Germany.

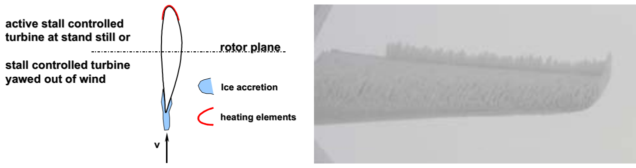


Fig. 5 Stall-controlled wind turbine in icing conditions at standstill: Possible configuration if only the leading edge is heated. Observation of trailing edge icing (right side) of a stall-controlled turbine at stand still.

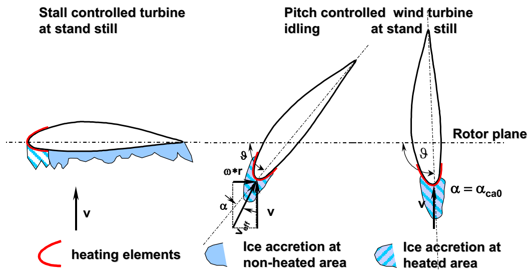


Fig. 6 Stall- and pitch-controlled wind turbine with heating elements at the leading edge during icing conditions at standstill and idling.

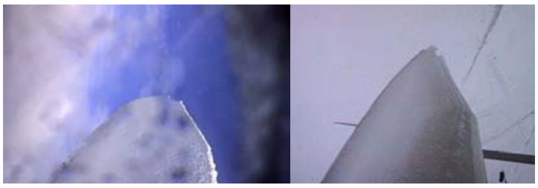


Fig. 7 Pictures taken by WEB camera from the hub of one of the Tauernwind turbines [1].

The left side of Fig. 6 shows a stall controlled turbine at standstill catching icing at low wind speeds with the rotor headed towards the prevailing wind direction. Even with heating elements at the leading edge an ice-free start with increasing wind speed will hardly be possible. The right side of the Figure shows the same situation for a pitch-controlled turbine in standstill or idling position. The activation of the heating system will de-ice the leading edge and enables the rotor to start energy production. However, during operation heating power in the range of about 2 percent of the turbine's rated power is needed to keep the leading edge free of ice [7]. If the heating is switched on during standstill or idling, higher prices for the energy needed have to be paid. Furthermore, the electrical heating elements - metal or carbon fibre made - can attract lightning strokes at an exposed location at the surface of the blade. Also the airfoil contour must be kept free from waviness to avoid unnecessary disturbances of the laminar flow around the leading edge during ice free conditions. The position of the heating elements at the leading edge involves additional problems. The rotor rotation in the gravity field causes typical high deterministic loads on the blade's structure. Aerodynamic driving forces and superposed so-called edgewise vibrations - caused by low damping of the natural frequency in this direction - are added to the gravity loads. Consequently, high strains in the GRP-load carrying girder as shown in [5] will cause even higher strain in the wires or fibres, respectively, of the heating elements. This will be especially true if the heating elements are carbon fibre made. Their Young's modulus is much higher compared to glass fibres of today's rotor blade structures. In other words the "heating fibres" take over the loads. Special technical solutions are required in order to avoid these effects and to avoid cracks in the heating elements.

7. Conclusions and Recommendations

Until today there are no standard solutions available on the market to keep the rotor blades ice-free or at least solutions for reliable ice detection as an information for the turbines' supervisory system. Consequently, today's rotor blades should be designed for the operation with ice accretion if the turbine is situated at sites with the risk of icing. The changed aerodynamic loads as described in [8] as well as the changed mass loads shall then be taken into account in the load assumptions. Provided that a reliable ice detector is available, the turbine can be set safely to standstill if icing events occur and put in operation again after automatical sensing of ice-free conditions. However, practical experience at the Tauernwind showed that all sensing systems tested reported different "ice information". A rather good instrument for detecting ice at the rotor blades seems to be a web-cam in the hub, as shown in Fig. 7, where the pressure side of an iced rotor blade can be seen. Even via internet, a camera cannot be used efficiently as ice detector, because it requires a manned campaign and good visibility also at night. For checking the blades' surface in order to compare ice detection with other instruments or to check for ice accretion before a manned restart of the turbine after icing events, the web cam seems to be an appropriate means for the time being. Some types of de-icing and anti-icing systems described above have been tested on prototypes or small serial production lines or are still under development. Thus, only little experience with anti-icing and de-icing systems is available compared to the large number of turbines being erected world wide. The size of the turbines is still growing and reaches easily 150 to 200 m with the blade in the upright position. These rotor blades can scratch low clouds and may collect ice even at coastal or offshore sites. But also the market for inland turbines, especially those with large towers, increases and requires standard solutions for operation during icing conditions. What has to be done? The principles of operation of wind turbines under icing conditions have been compiled in the EU-funded WECO project (Wind Energy Production in COld climate [1]). However, since finishing the research work, much more wind turbines of bigger size have been installed. Documentation of icing and its effect on the power production as well as on the ultimate and fatigue loads of the structures have to be carried out at certain research and demonstration projects on a pre-competitive basis in order to improve the theoretical background. This knowledge has to be used to improve the national and international Standards concerning cold climate operation. Reliable prediction of energy production and the fatigue loads on the turbine's components at inland sites can only be done if ice detectors deliver exact information about icing. Also the control system of the turbines has to rely on sound information on icing situations in order to shut the turbine down or react in another way to prevent the surrounding or the turbine itself from harm and damage. The reliable detection of ice is an indispensable requirement for the operation of wind turbines in cold climates. These ice detectors and ice free wind sensors need standardised conditions according to which they can be designed and calibrated. These standard conditions are not available yet and have to be defined. In order to fit the turbine economically to the site reliable information about possible icing is necessary. An adequate instrumentation is therefore of fundamental importance.

8. References

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