DE-ICING TESTING AND DEVELOPMENT OF ULTRASONIC WIND SENSOR FOR COLD CLIMATE

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ABSTRACT

The wind energy industry continuously upgrades requirements for the wind measurement in wind turbine control, power curve measurement, and site assessment applications. This is due to demand of producing more wind energy with reduced production losses. From this trend follows the increased hub height level of new wind turbines. In addition, more and more often new wind turbine installations are located in more severe environments. Thus, conditions for icing can occur more regularly. To meet the requirements of harsh weather conditions, continuous wind sensor evolution includes not only the implementation of the sensor de-icing system, but also the evaluation and development of testing methods and tools. In this paper, applied snowing and icing wind tunnel test facilities are represented and icing mechanisms are discussed. A scale model experiment was performed to study the temperature distribution on the surface. The de-icing development of the Ultrasonic Wind Sensor WMT700 is introduced. The sensor development work has led to the ultrasonic wind sensor with enchanced heating system, including the implemention of the sensor body heating for cold climate installations.

INTRODUCTION

There is increasing demand for wind energy production. This leads to larger turbines and increased hub height. In addition, more and more often new wind turbine installations are located in more severe environments, thus conditions for icing can occur more regularly. To meet these challenges, continuous wind sensor evolution includes not only the implementation of the sensor de-icing system, but also the evaluation and development of testing methods and tools. [1-5]

A wind turbine controller requires a functional wind sensor that provides correct wind speed and direction readings. The controller needs to optimize energy production for the energy grid and to protect a wind turbine from overload conditions. To maintain reliable wind readings with high data availability, the wind sensor has to be equipped with a sufficient de-icing system in cold climate installations. The essential aspects of the de-icing system are heat generation and associate sensor internal control logic. Prior to being able to design an appropriate de-icing system, one has to understand possible ice forming processes and to define appropriate design target.

Here, we study the original and the new modified de-icing system of the Ultrasonic Wind Sensor WMT700 in various laboratory conditions. The starting point is the icing processes including secondary icing followed by related test methods. A scale model of an ultrasonic wind sensor is studied under icing conditions. In addition, practical implementation issues are presented.

ICE TYPES

Environmental conditions affect ice formation. The parameters are air temperature, wind velocity, diameter of super-cooled water droplets, and liquid water content. Ice formation occurs when rain falls on a surface cooled below 0 °C, or when super-cooled raindrops freeze on a surface at impact. Table 1 shows the standard draft of the IEC that provides the categorization for ice formation. In addition to these primary ice formation phenomena, there is so called secondary ice formation. In the phenomenon of secondary icing, snow attaches to surface, melts, and freezes again forming a solid ice layer. [6-7]

The important aspects are event duration and total rainfall intensity. For instance, an intense event of very short duration can produce a limited amount of icing and thus its effect to operations might be relatively mild. Respectively, a mild icing event of a very long duration can cause a severe impact on operations. Table 2 presents typical droplet characteristics from condensation nucleus to typical rain. In practice, droplet size varies from 10 microns to 1000 microns. Droplet number in a unit volume varies depending on drop size and rainfall intensity. [8-9]

Events causing clear ice are very challenging, because of availability of free water is high per unit volume, low temperature enables freezing, ice adhesion to structure is strong, and high wind speed condition removes heat easily away from structure. The duration of these events is typically relatively short, while conditions of ice forming directly from cloud droplets may last weeks. In addition, secondary icing is important for areas with regular snowfall. All these icing cases are very interesting from de-icing point of view.

Table 1. Formation of ice according to IEC 60721-2-2 Ed.2 Draft. [6]

Type	Description
Air hoar	Air hoar is formed when moist air contacts a surface cooled below 0 °C and sublimes on it. Air hoar usually forms when wind velocity is low. It consists of needle-like crystals and its adhesion to the surface is weak.
Rime	Rime is formed as a result of repeated impinging and freezing of super-cooled water droplets carried by the wind against an object. It has a very characteristic appearance of "shrimp tails" because the points where it attaches to an object are small and grow windwards. Its color is white and it has a granular structure. Rime can occur simultaneously with snow causing a huge covering of snow on a suitable object.
Clear ice	Clear ice is formed when super-cooled raindrops freeze on a surface. It is hard and either opaque or transparent. It can form a layer-like structure of opaque and transparent layers with small air bubbles inside the structure. Clear ice has no particular visible structure. It is compact, its density is high and its adhesion force is strong. Clear ice is formed when the temperature is low and wind velocity is high.
Glaze ice	Glaze ice is formed when super-cooled raindrops fall on a surface and a water film is formed before freezing. Its density is high as well as its adhesion, and it has no air bubbles.

Table 2. Droplet sizes from condensation nucleus to rain drop. [8]

Droplet	Radius in microns	Number per liter	Terminal velocity [cm/s]
Condensation nucleus	0.1	10^6	0.0001
Cloud droplet	10	10^6	1
Large cloud droplet	50	10^3	27
Conventional borderline between cloud and rain droplets	100		70
Typical rain drop	1000	1	650

TEST METHODS

Typically, a test scenario of a wind sensor starts from wind measurement performance tests. Used performance tests should follow the ISO16622 and MEASNET methods, where laminar airflow is used to define measurement accuracy over measurement range of interest. In addition, structural strength for extreme wind conditions is studied. However, there is no adjustment for temperature of airflow. In fact, temperature of airflow can change especially with wind tunnels having inlet suction open to the outside of the wind tunnel building. The wind driven rain test follows performance tests. The intention is to study water intrusion and performance under heavy precipitation condition. The main parameter of the test is accumulated rainfall. Unfortunately, in the wind driven rain test airflow has typically uncontrolled vortexes and the variation of droplet diameters is large. [10-11]

The freezing rain test experiments, if a unit under test (UUT) withstands freezing conditions. Once the freezing condition is over, the interest is on the speed of recovery. Here the essential parameter is accumulated rainfall. Equally important is to have controlled sub-zero temperatures. The test method includes a cold soaking period (-18 Celsius degrees) before pre-cooled water (2 Celsius degrees) is sprayed at -7 Celsius degrees on top of a UUT. In some tests, a blower generates mild airflow. Even if airflow is measured, the actual airflow quality remains unknown.

To tackle unknown airflow quality and uncontrolled droplet size issues, the icing wind tunnel of the Kanagawa Institute of Technology, KAIT, was applied. Here an Eiffel type wind tunnel with open type test section was applied because of the bigger sectional area of the outlet of the wind tunnel. This icing wind tunnel provides the laminar airflow of 10 m/s. The droplet size is around 19 microns, which is similar to cloud droplets. In this experiment, the set ambient temperature is -12 Celsius degrees. The overall icing condition having liquid water content (LWC) of 0.3 g/m^3 is harsh and is able to grow severe ice layer over insufficiently heated structures.

The effect of attached snow was studied in the snowing wind tunnel of the National Research Institute for Earth Science and Disaster Prevention, NIED. A snow machine can produce large amount of artificial snow with dendritic shape similar to those of natural snow. Due to the simple mechanism of the snowfall device, the snowing intensity, namely the mass flux of the airborne snowflakes in the cross-sectional area of the test section, is altered by changing the sieves with the different size of mesh. Moreover, by the same reason, the regulation of the snowing intensity is limited. The snowing wind tunnel provides the laminar airflow of 6 m/s. The snow flux is almost 9 g/m^{2}s. The ambient temperature is -12 Celsius degrees.

To study de-icing capability of a UUT, there is need to control following test parameters: speed of airflow [m/s], quality of airflow, ambient temperature [C], rain intensity [mm/hour], liquid water content [g/m^3], droplet size [microns], snow flux [g/m^{2}s] if also snow is generated, and test duration [minutes]. Table 3 presents test conditions and parameters. There is a clear link from icing

Table 3. Examples of test conditions. Mark "-" indicates that parameter is not monitored.

Parameter	Wind (Aalto)	Wind driven rain (Toptester)	Freezing rain (Arctic test lab)	Icing (KAIT)	Snowing (NIED)
Airflow speed [m/s]	65	18	9	10	6
Flow condition	Laminar	Turbulent	Turbulent	Laminar	Laminar
Ambient temp [deg. C]	-	-	-7	-13	-12
Rainfall rate [mm/hour]	-	100	-	-	-
Icing rate [mm/hour]	-	-	25.4	-	-
LWC [g/m^3]	-	-	-	0.274	-
MVD [microns]	-	-	-	18.6	-
Snow flux [g/m^2s]	-	-	-	-	8.53
Duration [min]	45	30	270	40	30

processes (Table 1) via environmental conditions (Table 2) to test methods (Table 3). However, facilities providing test services are not able to simulate artificially all environmental conditions. There are limitations with available temperature ranges and droplet sizes, for instance. Regarding a wind sensor testing, there is need to control airflow conditions, such as laminarity level, airflow speed and direction variations. This is valid especially if the test method is applied not only for operative and withstanding tests but also for performance testing.

FREEZING MECHANISM

With the freezing rain test profile, the original de-icing system was operative first 27 minutes, and returned functional in 2 minutes after airflow was halted. To find out the freezing mechanism, original de-icing system was tested in the snowing wind tunnel of the NIED. In this experiment, the snowfall device generates snow flux from fresh snow created just before the test started.

The snow accumulates on horizontal surfaces. In addition, snow attaches to insufficiently heated structures. A video camera and a thermograph recorded icing development. Figure 1 presents the snowing wind tunnel. It was found out that the snowfall attached to the surface of the transducer stacks. After 10 minutes an ice bridge was formed from the top part of the transducer stack to the bottom part of the transducer stack. Figure 2 presents the ice bridge. Under the ice bridge, there was an air gap forming an acoustical barrier for airborne ultrasound. This resulted in an invalid measurement after 10 minutes. Even before this some sporadic anomalous measurement results occurred.

In more details, here ice formation of the original transducer stack is the consequences of the secondary icing. The secondary icing is a process, which occurs in icing and snowing environment. First snowflakes collide with or attach on the heated surface of a body of interest. Due to the heat from the surface, they melt and turn into the liquid phase. The molten water then flows leeward, downward with the drag force by the airflow. In the end, it reaches the unheated part of the surface and freezes to form an ice deposit. The difference of this type of ice formation from the ordinary icing is that there exists a melting-flowing process in between collision and freezing. The growth of ice from the lower part of the transducer stack is attributed to the upward accumulation of ice from the unheated surface of the bottom of the stack. For the growth in the upper part of the stack, the inverse process undergoes similar to the growth of an icicle. The important aspect is that an air gap between the ice and the surface exists, which may influence to the ultrasonic pulses between the transducers.

The icing wind tunnel of the KAIT was used to verify the test result with a video camera and a thermograph. Figure 3 presents the wind tunnel. The ice growths again from the top part of the transducer stack to the bottom part of the transducer stack as seen in Figure 4. Measurement readings were correct first 15 minutes even though slight variation was observed. After 15 minutes readings were invalid and they remind invalid.

To study the contribution of the surface temperature distribution, a scale model experiment in the snowing wind tunnel was performed. This dummy model of the transducer stack had an array of three heater elements. The model structure and heating options that were “centered”, “whole”, and “edge” are seen in the Figure 4. The outside diameter of the model was 30 mm and the length is 82 mm. The heating power in this experiment was 12W. The outer surface of the model was coated by a black-body paint for the thermograph measurements. The thermograph measurements revealed that in this experiment non-heated areas might be close to the freezing just before the onset of snowing test. Hence, after the test started, the temperatures in those areas might be around the freezing point. It can be deduced that the attached snowflakes melt, and ice accretes and grows. It was found out that only the heating option “whole” kept entire structure clear of ice formation.

Figure 1. Snowing wind tunnel set-up. Fresh snow is fed to snowfall device from where is falls down to the wind tunnel, where the unit under test is located.

Figure 2. Ice bridge forms to original transducer design in the snowing wind tunnel.

Figure 3. Icing wind tunnel set-up provides cloud droplets with airflow under sub-zero temperatures.

Figure 4. Ice growths from unheated structures of the original transducer design in the icing wind tunnel.

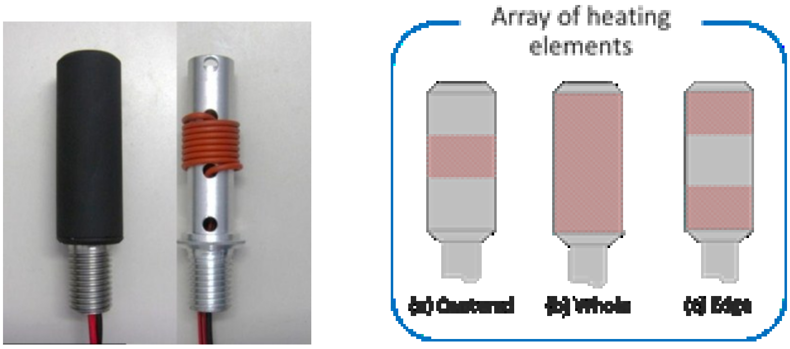

Figure 5. On left, the dummy scale model of a transducer stack had a wire heater embedded to a rubber. On right, the heating variation options of the dummy transducer stack were “centered”, “whole”, and “edge”.

Table 4. Heating voltage, sensor cable length, and cable type combinations are presented. Heating power supply requirement is 400W.

	Cable length				
	2m	10m	20m	30m	40m
Wire type					
0.5mm^2 / AWG20	24Vdc	28Vdc	-	-	-
1.0mm^2 / AWG17	-	-	28Vdc	30Vdc	32Vdc
1.5mm^2 / AWG15	-	-	-	-	30Vdc

EVALUATION OF MODIFIED VERSION

The evolution version of the Ultrasonic Wind Sensor WMT700 is used to study an enhanced de-icing system. The design focus is in ultrasonic transducer stack structure, sensor body heating, and heating algorithm. With transducer stack, the design challenges are several surface materials and complex internal structure. Different materials introduce variation on heat conductivity. The complex internal structure relates to very tight multi-layer structures and to the fact that very many structural components are multifunctional. A multifunctional component has several functions and may contribute to design features via mechanical, electrical, and acoustical means. [12-14]

Even though heat conducts from the arm heaters to the end cap of the sensor body, separate body heating improves the de-icing. In this design, the body heating consists of two separate components. They are the enclosure tube and the end cap to which sensor arms are connected. One heater element attaches to the enclosure tube and another to the end cap. This design is relatively complex not only because of added heater elements, but also due to overall power consumption that required new safety circuits for high currents.

The heater algorithm chanced because of new heating elements, modified heating balance, and enhanced control logic. New heating balance is about 30 Watts for transducer stacks, 120 Watts for arms, and 150 Watts for body heating when considering average power consumptions. A heater supply requirement for peak power is 400 Watts at 24 VDC. Since the heating components are resistive elements, the cable resistance is an important factor. Table 4 presents practical combinations for heating voltage, cable length, and wire type.

Regarding to the freezing rain test profile (Table 3) the finding was that the new modified design remained operative throughout the test period, while the original de-icing system was operative first 27 minutes, and returned functional in 2 minutes after airflow was halted. The modified design of the transducer stacks does not collect primary or secondary ice anymore excluding few ice droplets at the top of the transducer stack. The inactivated body heating generated severe ice accumulation over the sensor body. The accumulated ice was applied to define the icing rate. Figure 6 shows the icing test result that is ice free transducer stacks. The test was performed at the Arctic Test Laboratory, Finland.

With the icing test profile (Table 3), the finding was that the new modified design remained operative throughout the test period of 40 minutes. The modified transducer stacks remained free from ice bridges and secondary icing. The previous design was operative first 20 minutes, after which measurement readings were invalid. Figure 7 shows the icing test result that is ice free transducer stacks and sensor body. Figure 8 provides the measurement readout from the modified sensor throughout the icing test. The test was performed at the KAIT laboratory, Japan.

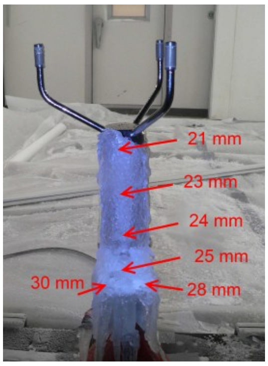

Figure 6. New sensor design was operative throughout the test period with the freezing rain test profile (Table 3). In this test, the body heating was inactivated.

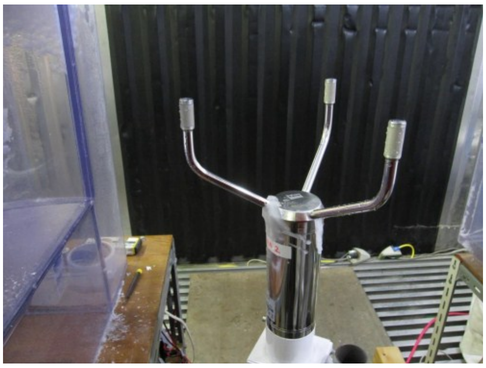

Figure 7. New sensor design was operative throughout the test period with the icing test profile (Table 3).

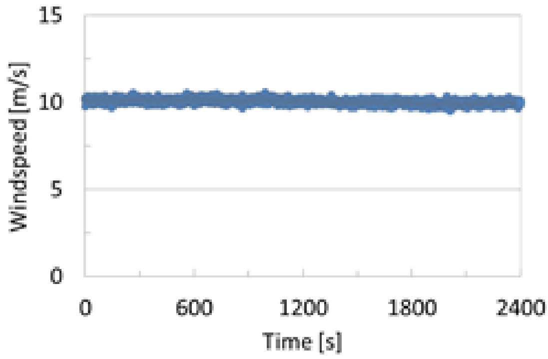

Figure 8. The WMT700 Ultrasonic Wind sensor with the new modified transducer stacks was operative throughout the icing test period of 40 minutes performed in the icing wind tunnel of the KAIT.

CONCLUSIONS

Quantitative evaluation of wind sensor is performed in icing and snowing conditions. Even though there is no one-to-one equivalency between real weather events and laboratory test methods, the existing test methods can be applied to develop and improve wind sensor's de-icing system. From test methodology point of view, the combination of various parameters like airflow, temperature, droplet size, and liquid water equivalent, is a challenging task to generate, especially if a wide range of parameter variation is looked for.

The modified version reveals performance without any invalid measurements. Thus, the enhanced de-icing capability of the Ultrasonic Wind Sensor WMT700 evolution version is clearly improved. The performance was improved due to the modifications on transducer stack structure, body heating, and heater algorithm. These modifications enabled to pass both the freezing rain test profile and the icing test profile.

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