Restricted
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General Description
Ice Impact on operation of Wind Turbines
- Risk and Mitigation -

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See general reservations, notes and disclaimers (including, Section 8 General Reservations, Notes and Disclaimers) to this general specification.

1 References

Ref.	Document title
[1]	*Wind Turbine Icing and Public Safety – a Quantifiable Risk?.* Colin Morgan and Ervin Bossanyi, Garrad Hassan, 1996.
[2]	*Risk Analysis of Ice Throw From Wind Turbines.* Henry Seifert, Annette Westerhellweg and Jürgen Kröning, DEWI, 2003.
[3]	*Wind Energy Projects in Cold Climates.* IEA Wind – Expert Group Study on Recommended Practices May 22, 2012
[4]	*Wind Energy Production in Cold Climate.* Tammelin, Cavaliere, Holttinen, Hannele, Morgan, Seifert and Säntti, 1997.
[5]	*General Specification VID.* Vestas Wind Systems A/S, DMS 0049-7921.
[6]	*General Description VAS* Vestas Wind Systems A/S, DMS 0068-6577
[7]	*General Specification VDS.* Vestas Wind Systems A/S, DMS 0060-8398.

2 General Description

Modern wind turbines are large structures with large surface areas where ice can form and accumulate under certain atmospheric conditions, such as ambient temperatures near 0°C, in combination with high relative humidity and precipitation. This is no different than for other large structures, such as transmission lines, bridges, buildings etc. The adhesion of the ice to the surface of the wind turbine varies depending on the formation conditions and the surface state, but since tower, nacelle, hub and blade surfaces are smooth, accumulated ice can shed from the turbine and fall to ground due to gravity. Accumulated ice can impact the power performance of the wind turbine.

In addition, and specifically for the blades of the wind turbine, ice accumulation is accelerated if the required atmospheric conditions are present and the turbine is in operation (i.e. the rotor is turning). This is because in rotation, the blades are forced into contact with increased amounts of moisture in the air and experience an increased surface wind chill. Ice accumulation on the blades can lead to ice throw in addition to ice shedding, where ice is not only falling approximately vertically down from the turbine, depending on wind speeds, but is also sliding off the rotating blades due to the rotational forces and thrown some distance from the wind turbine. This distance depends on the rotor speed, the wind speed and the constitution of the ice accumulation.

The related safety aspects of ice shedding and ice throw must be taken into account during project development, site operation and service.

The purpose of this General Description is to present information on the risk and offer recommendations for how to mitigate the risk, including explaining what turbine options are available for ice performance impact and ice risk mitigation

3 Icing Risk

Formation and accumulation of ice on the wind turbine structure is dependent on atmospheric conditions at the wind turbine installation site and the operation mode of the wind turbine. Fall of accumulated ice from a wind turbine at standstill or ice throw from a wind turbine in operation, can be caused by sudden changes in atmospheric conditions, such as ambient temperature, precipitation, wind or solar radiation.

It can also be caused by mechanical movement of the wind turbine structure due to vibrations, operating mode state changes, such as acceleration/deceleration, emergency stops etc. and it is impossible to predict when the individual discrete ice fall event or ice throw event occurs. Ice fragments, blocks, sheets or icicles may loosen and fall or slide off the turbine, making the area directly under the nacelle and rotor the highest risk zone [1].

The second highest risk zone is a surrounding circular area around the wind turbine, where ice throw may propel ice fragments away from the turbine. While the turbine will yaw around its tower vertical axis 360 degrees, there is typically a predominant wind direction for a given site and installation pad, so the ice throw risk is not uniform 360 degrees around the turbine but will be higher in some wind sectors than others. General guidance about this risk distribution is not possible since it depends on the site conditions for each project.

The distance ice fragments may be thrown from the wind turbine can be up to several hundred meters, depending on the conditions [1,2]. Any persons (general public or site personnel), buildings, installations, infrastructure, transport equipment etc. that are hit by falling ice fragments may sustain injury or damage respectively, if adequate protective measures are not ensured.

4 Icing Risk Mitigation

Risk of ice fall and ice throw must be considered during project scoping, project planning, project permitting as well as wind power plant operation and service. This includes wind power plants installed in densely populated areas, recreational areas, near roads, industrial areas etc.

Vestas has installed more than 69,000 wind turbines in more than 80 countries over the last 40 years (per September 2019), many of which are experiencing icing conditions for significant parts of the year. With this field experience combined with guidance from recognized industry practice [3], Vestas proposes the following actions to minimize the risk and impact of ice fall and ice throw for ice-prone wind power plant sites:

4.1 Managing Turbine Location

In the siting and permitting phase of a project, it should be made sure that the individual turbines are located a safe distance from general public recreational or occupational use areas, roads, buildings, installations, infrastructure, etc, or mitigations are in place to reduce risk under icing conditions to an acceptable level. Vestas always recommends a site-specific icing risk assessment, but if this is not possible, then general guidelines may be useful.

Certifying bodies DNVGL and DEWI recommend use of the reference “Wind Energy Production in Cold Climate” [4], which proposes the following rule for calculating a safe distance “d” for ice fall and ice throw, respectively:

Ice fall: $d = v \cdot (D/2 + H) / 15$

Ice throw: $d = (D + H) \cdot 1.5$

where d = safe radial, horizontal distance from turbine tower in m, D = rotor diameter in m, v = wind speed at hub height in m/s and H = hub height in m.

Site-specific safe distances may deviate from this general rule, depending on the design of the turbine, wind speed, rotor speed, blade surface state, atmospheric conditions and many other factors. The siting restrictions that an icing risk assessment may infer or which this general rule may infer, can be reduced by implementing an ice detection system to the turbine, which allows the turbine to be shut down in the event ice build-up is detected on specific locations of the turbine structure. The extent of such a reduction depends on the local conditions at a specific site.

4.2 Applying Guards and Visual Warnings

Shielding off a wind turbine or wind power plant with fences and warning signs can be a means of providing appropriate protection of site personnel and the general public [3]. Only a full access restriction with a surrounding fence will provide physical protection but may not be feasible for certain sites. Hence, site-specific risk assessments with appropriately scaled, site-specific risk mitigation measures should always be undertaken.

4.3 Assuring Safety of Operators

Accessing and working in and around a wind turbine under icing conditions always have to be based on a risk assessment and should be limited to the largest possible extent to minimize risk. Appropriate safety precautions for accessing a wind turbine under icing conditions include:

- Shutting down the wind turbine remotely
- Yawing nacelle to position the rotor opposite the side of the tower where the tower door is placed
- Observe if and where the ice is built up, taking this into consideration together with the direction of the wind, when approaching the turbine
- Starting the wind turbine remotely when work is complete.

4.4 Vestas Ice Detection™ System

To reduce the risk of ice throw (but not ice fall), the wind turbine can be shut down remotely when site personnel observe icing conditions and ice formation on the wind turbine. In practise, turbines are not subject to onsite surveillance so Vestas also offers automatic detection and shutdown of a wind turbine, through installation of either a conventional nacelle-based ice detector such as Goodrich or Labkotec or Vestas Ice Detection™ system (VID).

Vestas Ice Detection™ system (VID) employs state-of-the-art DNV-GL certified sensing technology including full integration with VestasOnline® SCADA for operation and alarm. A master-slave functionality is offered such that one ice detection system can control the automatic shutdown and restart of all wind turbines in a wind power plant. Master-slave functionality is available for use in regions where regulations permit it.

Ice detection is offered in two variants: a nacelle based system and a blade based system: Vestas Ice Detection™ system (VID). While the nacelle based system is simple, it does not provide the same detection level as a blade based system, because the correlation between nacelle ice formation and blade ice formation is weak. For this reason, nacelle based ice detection is only recognized in some countries. Also the nacelle based ice detection does not have the same DNVGL certification as Vestas Ice Detection™ system (VID).

The blade based ice detection is more sophisticated. It comprises an accelerometer in each blade which is connected to a hub mounted control box (Ice Detection Cabinet), which in turn is connected to the turbine's hub controller. The system will provide information on ice build-up on the full blade and stop the turbine operation (production) when certain conditions are met, primarily that the ice build-up is above an adjustable threshold and the temperature is below 5°C.

Ice detection on the blade is measured as a mass increase of the blade. Mass changes lead to deviations of natural frequencies of lower modes of the blade. With the accelerometers in each rotor blade, the system continuously and automatically monitors specific natural blade frequencies. When the detected frequency deviations exceed predefined thresholds, warning and alert signals are issued to the turbine controller.

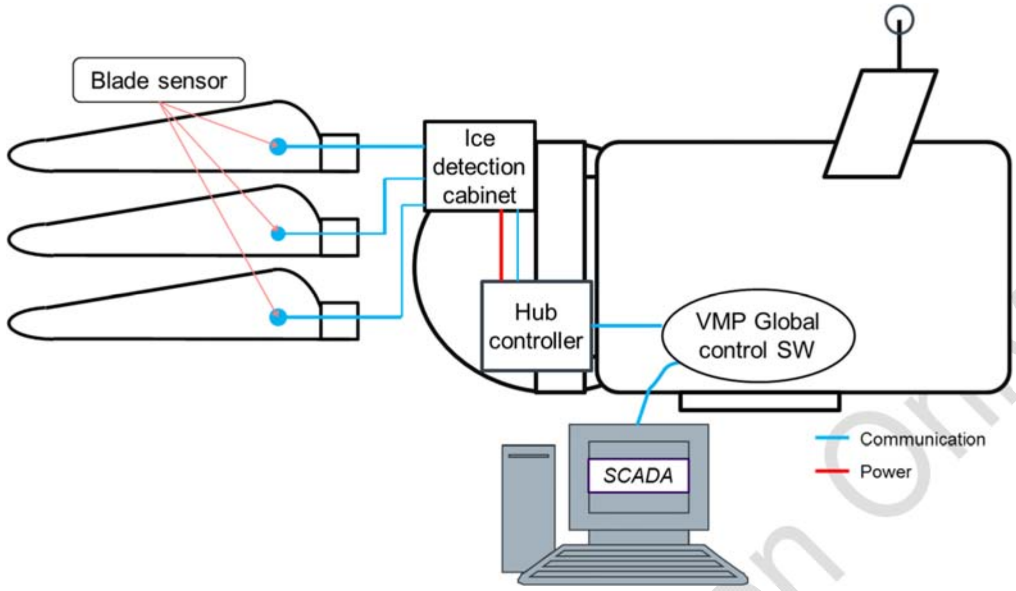
Ice detection thresholds based on the achievable frequency resolution of the system is set to default values, but may be adjusted to local climatic characteristics and regulations to further reduce ice throw risk.

Ice detection is executed continuously with the turbine in operation / production and at standstill, leading to a real-time detection of ice formation on the blades.

The blade based ice detection system continuously signals the icing condition of the blades as well as its own system status to the turbine controller. According to these signals the controller can automatically shut-down the turbine in the case of an ice alert signal and automatically restart the turbine after the ice-alert has been lifted. Via the provided signals the controller can also check the validity of the received ice status signals and react accordingly.

After turbine shutdown due to detected ice formation, the system continues its measurements at standstill. Thus, prior to a restart of the turbine, the absence (or just a noncritical remainder) of ice can be confirmed and the controller can then automatically start-up the turbine.

The layout of the blade based ice detection system is shown in the figure below.



Other means of ice detection exists, such as power curve degradation monitoring, detection of rotor imbalance caused by blade ice formation by a main shaft vibration sensor, but since ice can build up in a symmetrical manner such a situation will not trigger the sensor. Since, Vestas' blade based ice detection system has an individual sensor in each blade, symmetric ice formation will still be detected.

IMPORTANT Ice detection technology is still new and relatively immature, so despite carrying certification, ice detection systems that cause the turbine to shut down do not provide a detectability of 100%. Therefore, equipping a wind turbine with an ice detection system cannot be regarded as a guarantee of prevention of ice throw. It will, however, reduce the ice throw risk as also recognized by authorities in several countries.

When ice formation is detected and trigger levels exceeded, the turbine performs the following actions:

1. Ice warning to wind turbine controller and VestasOnline® SCADA but no change of wind turbine operating mode.
2. Ice alarm to wind turbine controller and VestasOnline® SCADA triggering shutdown of the wind turbine.
3. Revocation of the ice alarm state when icing conditions disappear and blade mass is reduced below triggering threshold and automatic or manual restart of the wind turbine, depending on the control settings.
4. Optionally, and provided that either the Vestas Anti-icing™ system or the Vestas De-icing™ system is installed, the ice detection signal can be used by the turbine controller to trigger their activation.

The ice detection system signals the hub controller to shut down the turbine. If the ice detection system is not able to measure ice (for example due to a sensor failure) the turbine will be stopped automatically if the ambient temperature is below 5°C.

A 24 VDC output is available in the ground controller which can signal to connected customer installed external equipment (warning sound, warning light etc.) when the wind turbine is stopped by the ice detection system.

For further details on Vestas Ice Detection™ system, please refer to the General Specification [5] or contact Vestas.

5 Cold Climate Effects on the Wind Turbine

Vestas has wind turbines that are designed for survival in temperatures as low as -40°C and operation down to -20°C. A Low Temperature package is available as an option that allows the wind turbine to operate down to -30°C. These temperature ranges are applicable irrespective of icing.

Ice loads are considered in the wind turbine design loads according to DIBt 2012 and reflected in the loads evaluation. The DIBt 2012 ice load cases are also applied to the IEC design loads.

The wind turbine is equipped as standard with a tower top accelerometer that protects the structure from overloads. Similarly, each blade is equipped with load sensors that will stop the turbine if loads or rotor balance are not within threshold limits. While these protection features are in place and will protect the turbine from all load events, including icing, they are not expected to be triggered by icing events as it is very unlikely that ice accumulation can be severe enough to approach the trigger levels of the tower and blade load sensors.

Icing on wind sensors or blades will affect the power production of the turbine. Icing on wind sensors will lead to a wrong measurement and correspondingly wrong operating response from the wind turbine that affects power production negatively. Ice build-up on the blades will affect the lift and drag coefficients of the blade and reduce the power production.

For mitigating power production deterioration due to icing on wind sensors, Vestas employs heating elements in the ultrasonic wind sensors.

For mitigating power production deterioration due to icing on blades Vestas offers either the Vestas Anti-icing™ system (VAS), or the Vestas De-icing™ system (VDS) – dependent on turbine model. These are explained in further detail in the next sections.

6 Vestas Anti-icing™ System

The Vestas Anti-icing System™ (VAS) is a fully integrated turbine system designed to prevent and actively remove ice build-up on wind turbine blades. The VAS heats targeted areas of the blade to prevent and remove any ice accretion when activated, thereby limiting blade aerodynamic performance degradation and consequent sub-optimal wind turbine generator (WTG) power production.

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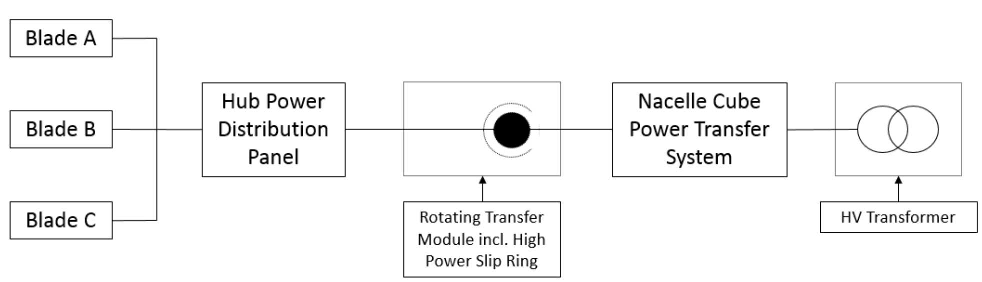
IMPORTANT The Vestas Anti-icing™ system is designed to improve turbine power production in cold climate conditions and is a performance enhancement. It is not designed for eliminating or reducing ice fall and ice throw risks.

The VAS comprises of:

- A number of electro-thermal heating (ETH) elements embedded within the blade shell laminate in targeted areas.
- The ETH elements are controlled by the turbine controller in the WTG, which will identify and switch on and control the power the ETH elements dependent on the severity of the icing conditions.
- The control method permits the opportunity to vary the power dependent on the environmental conditions in which the WTG operates.
- The VAS is activated automatically based on a detected degradation in turbine performance (Power Curve Ice Detection (PCID)) and environmental factors (e.g. below a threshold operating temperature), a signal is sent to the turbine in order to activate the heating system. Provision of manual activation is provided for specific operational needs.
- The system operates while the WTG is in production and rotating, so called anti-ice mode, or in the most severe conditions the WTG is stopped and the heating performed on the stationary rotor, so called de-ice mode.
- The power is provided by the turbine through a nacelle-hub power transfer system that allows the ETH elements to be powered whilst the rotor is spinning or when it is stationary.



- The control and monitoring of the VAS is fully integrated into the turbine controller. Safety monitoring functions run continuously in parallel to ensure that the VAS operates within appropriate heating and environmental limits.

The VAS is automatically triggered via the use of Power Curve Ice Detection (PCID), with an additional option for manual activation by the operator.

The PCID is a software (SW) algorithm that is located in the VestasOnline® Supervisory Control and Data Acquisition (SCADA) system which compares the current WTG power performance to a nominal reference power curve delivered by Vestas, ambient conditions (i.e. temperature and wind speed), and general logging information from the WTG.

The reference curve, is configured to match individual turbine performance, and is based on ice-free data.

Based on a detected degradation in WTG power performance compared to the reference power curve, an activation command is sent to the WTG. This feature can be both enabled and disabled. In cases where it is disabled, it is possible to send a manual activation trigger signal from SCADA to the WTG.

The power curve degradation level at which the system will trigger an anti--icing command is configurable, together with the minimum wind speed and maximum ambient temperature at which automatic triggers can happen. The degradation level can be configured for individual wind speed intervals, to allow for lower trigger levels at low wind speeds, to compensate for increased statistical variance in the power curve.

The sequence of operation of the VAS (Operational Mode):

1. A Power Curve based Ice Detection (PCID) operating via the VestasOnline® SCADA system, detects a reduction in turbine performance below a set threshold.
2. The park level VestasOnline® SCADA system issues an anti-icing command to the turbine.
3. Based on the anti-icing command, the turbine controller activates the anti-ice heating.
4. At recovery of the grid power production to a defined fraction of the nominal reference power curve, the turbine will halt the heating process.

The anti-icing system can operate within the following ambient conditions:

- Ambient temperature between -20°C and +10°C.
- Wind speed below WTG cut-out - 25 m/s (anti-ice operational mode)
- Wind speed below 13m/s (de-ice operational mode).

7 Vestas De-icing™ System

Vestas De-icing™ system (VDS) maximizes energy production in icy conditions, by employing air heaters to force hot air through the blade interior volume heat up the blade surface. With full VestasOnline® SCADA integration, the system continuously monitors turbine power curve performance. Via the systems' automatic control, the wind turbine will only engage in de-icing when there is a net power production gain from doing so.

The basis for a de-icing blade is a standard blade. Modifications are made to allow for circulating hot air inside the blade cavities. Additionally a Hot Air Installation unit (HAI) is integrated in the root of each blade. The HAI unit comprises of ducting, a fan unit and heater units. Air inlet and outlet from the HAI are connected via flexible ducting to the blade cavities of the de-icing blades. To ensure optimal efficiency, the Vestas De-icing™ system is designed to de-ice the outer third of the turbine blade full chord and the remaining two-thirds of the leading edge towards the tip.

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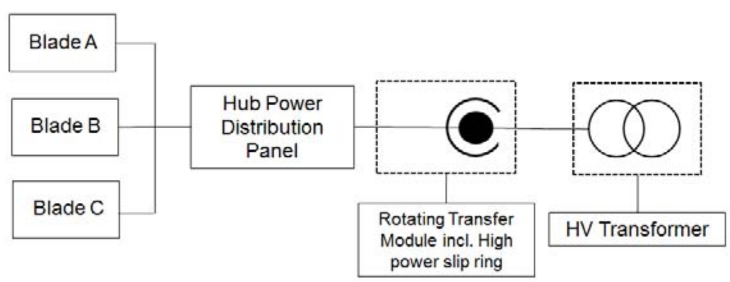
IMPORTANT The Vestas De-icing™ system is designed to improve turbine power production in cold climate conditions and is a performance enhancement. It is not designed for eliminating or reducing ice fall and ice throw risks.

All mechanical and electrical parts of the system are accessible from the turbine hub and root of the blade itself, making it safer and more convenient from a service perspective to maintain the system. The fan and heaters are serviceable parts, each of them individually removable from the HAI. Service can be bundled into the annual service schedule of the turbine.

The de-icing system draws power directly from the high voltage transformer (a step-down transformer is used in the Mk3E to allow for the increase in voltage on the HV transformer on that platform). The layout of the VDS power system is as indicated in the figure below:



The VDS can be configured for automatic activation via VestasOnline® SCADA, with an additional option to activate manually by a VestasOnline® SCADA operator. The automatic activation is based on a power curve degradation algorithm, comparing current turbine power performance to a previously defined turbine-specific reference curve, which is delivered by Vestas. Based on a detected degradation in turbine performance compared to the reference curve, a de-icing command is sent to the turbine, provided all turbine safety and operational envelope checks are okay.

The reference curve can be configured to match individual turbine performance, and is based on ice-free data.

The power curve degradation level at which the system will trigger a de-icing command is configurable, together with the minimum wind speed and maximum ambient temperature at which automatic triggers can happen. The degradation level can be configured for individual wind speed intervals, to allow for lower trigger levels at low wind speeds, to compensate for increased statistical variance in the power curve.

Additional to VestasOnline® SCADA activation, the VDS can be activated locally in the turbine, via the turbines operator panel.

The turbine will be paused with the rotor stationary during a de-icing cycle. All three blades will be heated up at the same time.

The sequence of operation of the VDS is as follows:

1. A Power Curve based Ice Detection (PCID) operating via the VestasOnline® SCADA system, detects a reduction in turbine performance below a set threshold.
2. The park level VestasOnline® SCADA system issues a de-icing command to the turbine.
3. Based on the de-icing command, the turbine enters into its de-icing cycle.
4. After the end of the de-icing cycle, the turbine may be manually or automatically put back into operation (Customer setting).

The de-icing system can only be activated when the following conditions are met:

- Ambient temperature between -15°C and +7°C.
- Wind speed below 13 m/s.

Automatic activation of the de-icing system will only allow 3 de-icing cycles within a 24 hours period; however manual activation can be done more frequently.

For more information about the Vestas De-icing™ system and the operational envelope, please refer to the General Specification [6] or contact Vestas.

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8 General Reservations, Notes and Disclaimers

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- This document, General Description, is not an offer for sale, and does not contain any guarantee, warranty, promise, commitment, representation and/or verification by Vestas, whether express or implied, including, without limitation, in respect of the effect of icing events on the wind turbine performance and structural integrity, are hereby expressly disclaimed by Vestas.
- Images and illustrations in this document may differ from the actual design.
- VID supports reducing the risk of ice throw, but is not designed to reduce the risk of ice fall, ice drops and/or ice fall; any use of, or reliance on, the system for such purpose is at recipients own risk. The risk of ice throw, ice drops and/or ice fall caused by operation of the wind turbine and operation of the VID is solely the responsibility of the customer.
- VAS and VDS are not designed to reduce the risk of ice throw, ice drops and/or ice fall; any use of, or reliance on, the system for such purpose is at recipients own risk. The risk of ice throw, ice drops and/or ice fall caused by operation of the turbine and operation of the VAS or VDS is solely the responsibility of the customer.
- For VID, actual icing and site conditions have many variables and states (for instance ice storms or ice due to rime accretion) and these differences when compared to the threshold level of VID may have an impact on VID performance.
- For VAS or VDS, actual climate and site conditions have many variables and should be considered in evaluating VAS or VDS performance. The design and operating parameters, as well as any estimated power curve performance, do not constitute warranties, guarantees, or representations as to VAS or VDS performance at actual sites.