A Comparison of Three Different Anti- and De-Icing Techniques Based on SCADA-Data

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***Abstract*: This work is a master thesis done within the master program in energy systems engineering at Uppsala University and in cooperation with OX2. The aim is to compare the operation and performance of three different anti- and de-icing systems (ADIS) for wind turbines (WTGs) during the winter 2014/2015. The systems evaluated are de-icing with heating resistances, de-icing with warm air and anti-icing with heating resistances.**

Inconsistency in the operation of the wind WTGs and the ADISs as well as lack of information made it hard to compare the efficiencies of the systems. The systems showed tendencies to improve the production. Especially examples during single ice events where the systems increased the power output were found, but the examples also showed possible improvements regarding the size of the systems and the duration of the de- or anti-icing cycles. Based on the approximated gain in production, during the studied time period, none of the systems could be determined to be profitable. The gain in production does however not have to be especially large for the systems to become profitable, and the results could be very different in a year with more ice, higher electricity prices or a more consistent operation of the systems.

Important characteristics of the systems were found to be the duration of a cycle, the energy required for the operation of the system and the trigger-point for activation of the system. Additional benefits like for instance decreased loads, risk for standstill and ice throws could also be provided by the systems.

Keywords: ice, anti-icing, de-icing, losses

Legend and Abbreviations

ADIS	*Anti- and De-Icing Systems.*
Anti-icing systems	*Systems that prevents ice accretion on the blades of the WTG.*
De-icing systems	*Systems that aims to remove ice from the blades once already formed.*
Overproduction	*Production higher than expected, due to for instance frozen anemometers.*
Production Loss	*Output lower than expected according to the power curves.*
Wind Farm 1	*Wind farm with a de-icing system based on heating resistances.*
Wind Farm 2	*Reference to Wind Farm 1.*
Wind Farm 3	*Wind farm with a de-icing system based on warm air.*
Wind Farm 4	*Reference to Wind Farm 3.*
Wind Farm 5	*Wind farm with an anti-icing system based on heating resistances.*
Wind Farm 6	*Reference to Wind Farm 5.*
WTG	*Wind Turbine Generator*

Introduction

A. Background

Ice accretion on the blades of the Wind Turbine (WTG) causes a lower energy production compared to the energy production in the same wind conditions with no ice, and thereby results in a loss of income for the owner of the WTG. WTGs in cold climates, like the climate in the north of Sweden, could have an anti- or de-icing system (ADIS) installed to prevent losses due to ice. In this report anti-icing refers to systems that aim to prevent ice from forming on the blades of the turbine whereas de-icing refers to systems with the strategy to remove ice once it already has been formed on the surface. Since there is no general technique for ADIS, it is of interest to learn more about the operation and efficiency of different de- and anti-icing systems, in order to minimize the losses and maximize the income of a wind farm.

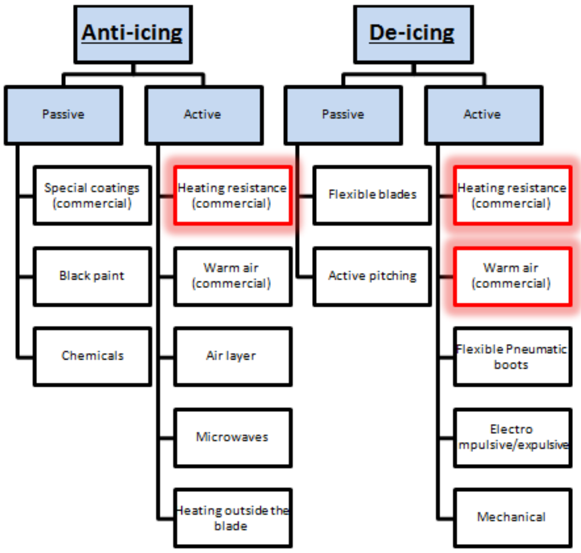


Figure 1: Overview of different de- and anti-icing strategies. The evaluated techniques in the report are marked in red (anti-icing with heating resistancs, de-icing with heating resistances and de-icing with warm air).

B. Aim

This work is a master thesis within the master program in energy systems engineering at Uppsala University and covers 30 credits. The thesis is done in cooperation with OX2, a privately held Swedish company active within the renewable energy sector. The aim of the work was to compare the operation and efficiency of three different ADISs installed in three wind farms operated by OX2 in Sweden. The de- and anti-icing techniques that were evaluated are de-icing with heating resistances, anti-icing with heating resistances and de-icing with warm air (in red in Figure 1). The main focus has been to evaluate the production of the wind farms during the winter 2014/2015. The performance was evaluated against the production in conditions considered to be free from ice, against a wind farm nearby the evaluated wind farm without an ADIS installed (reference farms) and against the other ADISs studied.

I. Method

Today production losses due to icing are calculated with many different methods. IEA Task 19 - Wind energy in cold climates, a working group within IEA Wind, are currently working on a standard method (T19IceLossMethod) to evaluate the production losses due to icing [1]. In this work a MATLAB-code was produced based on the main outlines in the proposed standard, with some alterations.

The parameters being used for the evaluation are wind speed, wind direction, ambient temperature, the power output and the state of operation of the turbine. The power output is compared to the output in conditions considered to be ice free, as a first approximation by constructing turbine specific power curves from measurements corresponding to temperatures above +3 °C [1]. In this work wind bins of 1 m/s and 90 ^{O} were used to construct the power curves.

Three types of icing events are identified in the evaluation:

- ***Type A)*** Loss of production
- ***Type B)*** Turbine standstill due to icing or operation of the de- or anti-icing system
- ***Type C)*** Ice influenced wind anemometer resulting in overproduction compared to the power curve.

For all three types of icing events to start, a temperature below 0 $^{\circ}$C is required. There are no temperature requirements for the rest of the ice event. Ice events of type A (production losses) occur if three following measurements (10-minute averages) of the power output are below the 10th percentile (P10) and last until three following measurements are above the P10. Ice event of type B (stand still) start if one measurement is below P10 and the following two measurements indicate a stop of the WTG, i.e. the mean power output is less than 0.5 % of the rated power. The event stops when three following measurements are above P10. Ice event C (overproduction) begins when three following measurements are above the 90th percentile (P90) and ends if three following measurements are below P90 [1]. In the code used, stops of the WTG are identified by the operation state of the WTG instead of limits in the power output as proposed in the standard. The reason for this was to make the calculation of the losses more manageable later on.

The identified ice events are removed from the complete data set and new power curves are constructed. Based on the new power curves, which contain "winter conditions", the final ice events are identified as above. Losses in the production are calculated for icing events of type A and B. The reference production during icing event C cannot be estimated since there is no knowledge about the accurate wind speed [1]. The loss of production during ice event A is defined as the difference between the reference production according to the reference power curve and the actual output and the loss during ice event B is defined as the reference output according to the power curve together with the power input for running the de- or anti-icing system.

A. Validation of the model

In order to validate the estimation of ice losses, data from one summer month (July) and one winter month (December) were compared, see **Error! Reference source not found.**2. Because of lack of data and time this was only done for one evaluated wind farm (Wind Farm 1). It can be seen that the data in July (blue) is much less spread than the data in December (red). The losses for both months were calculated for each WTG by taking the difference between the power curve and the output for all values under P10 for December (green). In July the loss was then found to be 0.7 % of the monthly production on average for the WTGs with a standard deviation of 0.6 % between the WTGs. In December the losses was 5.0 % on average, with a standard deviation of 0.7 %. All WTG stops were removed from the data sets.

Since there are few measurements from July under the power curve, the most common cause for the measurements under the curve in December is probably ice. Deviations could however also be caused for instance by increased turbulence etc. According to the result there are some measurements that will be treated as ice losses that are caused by other factors. For Wind Farm 1 this is about 1 % of the monthly production. This is however without considering the requirement for three following measurements to indicate the start of an ice event, which possibly could reduce the number further. The results are also without the requirement of a temperature below 0 $^{\circ}$C for an ice event to begin, since this obviously would result in no losses during the summer.

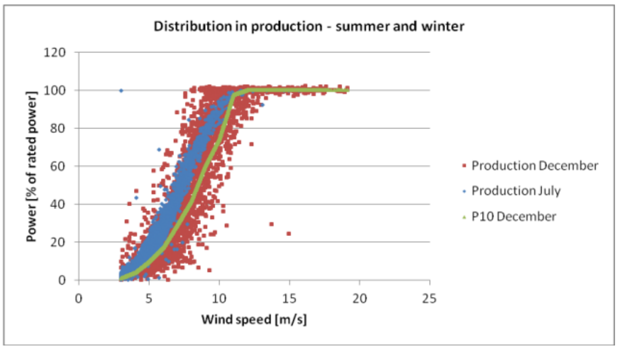


Figure 2: Distribution in production for summer (blue) and winter (red) measurements. The figure shows that most measurements under the P10 (green), in December, probably are due to ice. About 1 % of the measurements in July are however also under the P10 for December, indicating that there are some measurements that will be wrongly identified as ice losses.

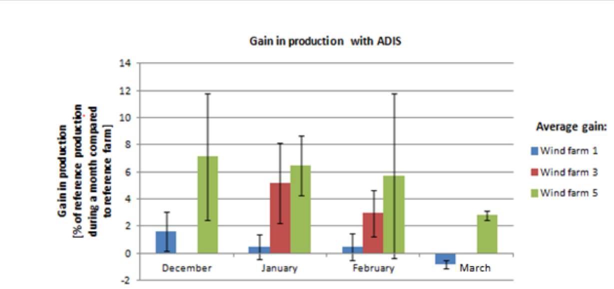
II. Results

A. Characteristics of the Studied Systems

Wind Farm 3 (de-icing with warm air) has the lowest installed power for operation of the system in relation to rated power, whereas the system in Wind Farm 5 (anti-icing with heating resistances) has the highest installed power as well as the highest range of power installed. The de-icing system in Wind Farm 3 is the only system using warm air, and the thermal efficiency could therefore be expected to be lower compared to the other two systems according to theory. The de-icing cycle in Wind Farm 3 was found to often be about 5 hours longer in comparison to Wind Farm 1 (de-icing with heating resistances), and the de-icing system in Wind Farm 3 is the only system which treats one blade at the time. Due to the longer de-icing cycle in Wind Farm 3, the availability could be decreased, which would be important if wind conditions are good. Since the winter is the time of year with most wind, according to theory, availability is therefore important. If the duration of a cycle can be altered through the control system this would be avoided, but this doesn't seem to be the case in the examples found. The fact that one blade at the time is de-iced in Wind Farm 3, also speaks against this, since stopping the de-icing cycle probably could cause imbalances. The system in Wind Farm 1 had a lot more starts per WTG during all months except March compared to Wind Farm 3, which probably is because the studied time period was a test period in Wind Farm 3. Information about the length of the anti-icing cycles and the number of starts during the studied months was not available or possible to identify based on the given information in Wind Farm 5.

B. Impact of Having the De- and Anti-Icing Systems Installed

Based on the approximated losses calculated for each wind farm, the possible "gain" of having the de- or anti-icing systems installed during the evaluated winter (in relation to the reference wind farms) are illustrated in Figure 3. The error bars are describing a confidence interval of 95 %, which means that the difference between the average losses of the two wind farms will be found within the extremes ("lowest gain" and "highest gain") with a certainty of 95 %.



Wind farm	1	3	5		1	3	5		1	3	5		1	3	5
Highest gain:	3,1		11,8		1,3	8,1	8,7		1,4	4,6	11,8		-0,5		3,1
Average gain:	1,6		7,1		0,4	5,2	6,5		0,4	2,9	5,7		-0,8		2,8
Lowest gain:	0,1		2,4		-0,5	2,2	4,3		-0,5	1,2	-0,4		-1,1		2,4

Figure 3: Outcome of having the de- and anti-icing systems installed during the winter 2014/2015. The colored bars show the average production gain in relation to reference wind farms. The error bars are illustrating a confidence interval of 95 %. Energy for operation of the systems is not included for Wind Farms 3 and 5

It can be seen that in the "lowest gain- scenario" i.e. the lower end of the confidence interval, there is no gain of having the system in Wind Farm 1 (de-icing with heated resistances) during the studied period compared to the reference wind farm. This is probably partly because the losses in the reference wind farm (Wind Farm 2) were small as well. In the "lowest gain scenario" the systems in Wind Farms 3 and 5 (de-icing with warm air and anti-icing with heating resistances) show a small gain compared to the reference wind farms, in all cases except Wind Farm 5 in February probably because of the large variation in the corresponding reference wind farm (Wind Farm 6). Energy for operation of the systems in Wind Farms 3 and 5 is however not included, and the bars should be somewhat lower. Since the gain is small, none of the systems can, for certain, be said to be advantageous in this scenario when considering the energy for the operation of the systems. In both the "average gain-" and the "highest gain-scenario" all systems perform better than the reference wind farms, except Wind Farm 1 in March, since the loss in the corresponding reference wind farm was close to zero.

The system in Wind Farm 5 appears to have the highest gain of all systems, but has at the same time the largest variation, which is probably due to a large uncertainty due to lack of data and information. Also Wind Farm 3 is showing a large variation, which could be due to the large uncertainty due to a small number of WTGs and inconsistent operation of the de-icing system. The WTGs in Wind Farm 1 do not show an apparent gain during the studied time period, the confidence intervals are however small, indicating a small variation between the WTGs.

B. Examples of Production During Single Days

Below, the production from one WTG in each wind farm is compared during a day. The purpose with these examples is to get an understanding of the operation of the de-icing system during single ice events.

B.1 Example - Wind Farms 1 & 2

During the 22nd of December the losses during the day for the studied WTG in Wind Farm 1 (de-icing with heating resistances) were about 50 % compared to the reference output, and the losses for the WTG in Wind Farm 2 (reference) about 81 %. It can be seen in Figure 5 that the WTG in Wind Farm 2 was still for 16 hours and the reference output was not achieved during the day. Since there were no error messages or manual stops and the wind speed was above cut-in wind speed, the stop was probably due to ice. The de-icing system of the WTG in Wind Farm 1 was activated 9 times, marked 1-9 in Figure 4, and for each de-icing cycle about 3 % of the rated power was used for the operation of the de-icing system. The de-icing cycles lasted for 40 minutes in all cases but one, where it lasted for 60 minutes. Between cycles 2 and 9 the de-icing system was reactivated within 20-40 minutes after the end of a cycle. The reference power was achieved about 1.5 hours after de-icing cycle 9. The many starts of the system indicate that one de-icing cycle does not ensure that the production reaches the reference output and perhaps there is room for improvement regarding power, control etc.

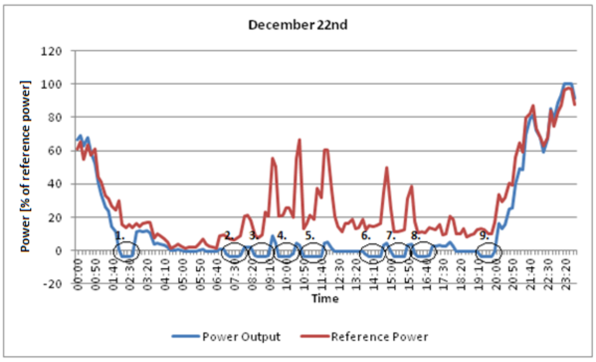


Figure 4: Output of a WTG with de-icing, during the 22nd of December. The de-icing system was started 9 times, marked 1-9 in the figure. The loss was about 50 % compared to the reference output. At 21:30 the production was 87 % of the reference output.

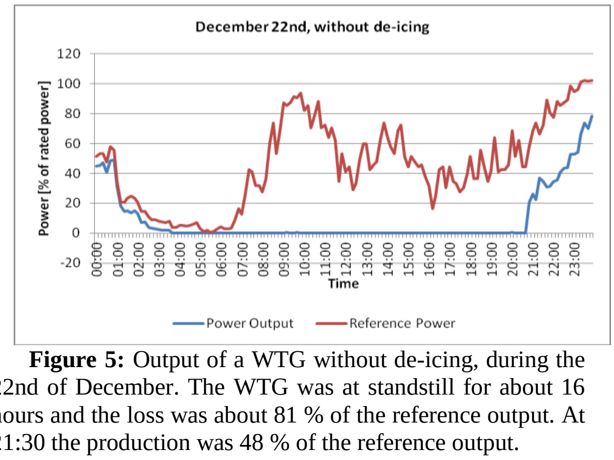


Figure 5: Output of a WTG without de-icing, during the 22nd of December. The WTG was at standstill for about 16 hours and the loss was about 81 % of the reference output. At 21:30 the production was 48 % of the reference output.

B.2 Example - Wind Farms 3 & 4

During the 1st of February the loss for the WTG in Wind Farm 4 (reference) was about 34 % during the day, see Figure 7. The de-icing system of the WTG in Wind Farm 3 (de-icing with warm air) was started 3 times during the day, see Figure 6, and the loss was about 76 %. If the energy for running the de-icing system is included the loss is about 77 % instead. Each de-icing cycle takes about 6 hours. After the first cycle the output is a maximum 45 % of the reference output and after the second de-icing cycle 55 % of the reference output. This indicates that the de-icing system was not able to remove the ice.

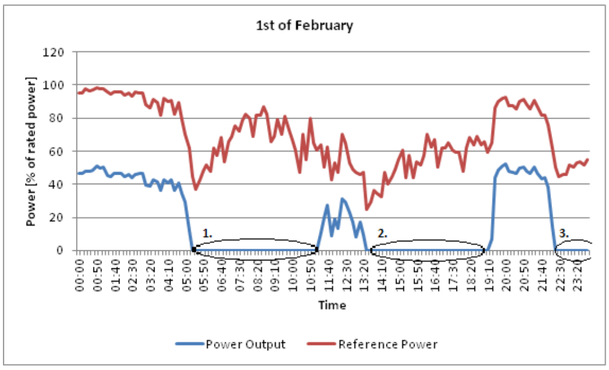


Figure 6: Output with de-icing system, 1st of February. The losses during the day are about 77-76 % of the reference output. At 20:50 the output is about 55 % of the reference output.

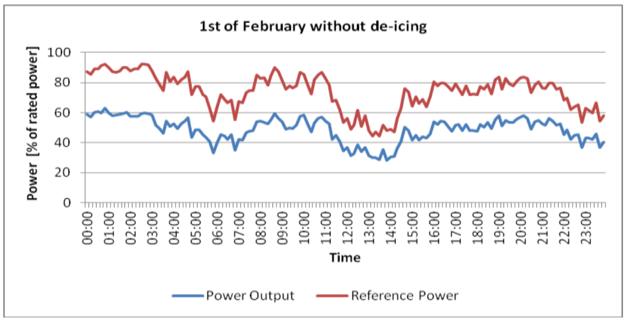


Figure 7: Output without de-icing, 1st of February. The losses during the day are about 34 % of the reference output. At 20:50 the output is about 68 % of the reference output.

B.3 Example - Wind Farms 5 & 6

There is no information about the operation of the anti-icing system in Wind Farm 5 and the length of the anti-icing cycles and the number of starts during the studied months was not possible to identify. It was therefore not found to be of interest to illustrate the production with an example

III. CONCLUSSIONS

In this work a MATLAB-script for evaluating losses in production of WTGs due to ice was created according to the main outlines in a standard proposed by IEA task 19. The losses due to ice, between December 2014 and March 2015, were then estimated in three wind farms with de- or anti-icing installed and three additional wind farms without any de-or anti-icing installed.

From the evaluation, it is evident that all studied sites are subject to ice. Based on the results obtained the three wind farms with a de- or anti-icing system installed show a tendency to improve the production in comparison to the evaluated reference parks. The quantification of the losses are however influenced by the model for evaluation, inconsistent operation of the systems and the WTGs, inconsistent data reporting and lack of information about the studied systems. It was therefore not possible to compare the efficiencies of the three systems.

In particular, one of the studied systems (de-icing with heating resistances) could be shown to improve the production during single ice events, which shows the potential of having a de- or anti-icing system installed. The results also indicate that the de-icing system with warm air not is sufficient enough, this could however partly be because the studied time period was a testing period of the system. The information about the anti-icing system with heating resistances was too sparse to evaluate the system. The studied examples showed possible improvements regarding for instance size and duration of the de-icing cycles, reflecting the limited experience of the operation of the systems. With a couple of more years of experience, the operation of the systems may become more efficient and profitable.

Based on the approximated gain (between December and March) none of the studied systems can, for certain, be said to be profitable with today's electricity prices. The evaluation is however entirely based on the difference in losses compared to the reference wind farms and is very uncertain. The conditions could be very different in a year with more icing and higher electricity- and certificates prices. A longer time period therefore needs to be studied and more information about the operation of the systems is needed in order to determine the profitability and efficiency of the systems. Considering de- or anti-icing systems when establishing wind farms at locations with similar ice conditions is recommended. Important characteristics are then energy for operation of the system, duration of one de- or anti-icing cycle and when the systems are activated. Important to consider is also possible additional benefits of the systems as for instance increased availability, decreased risk for stops, loads and fatigue of WTG components as well as safety aspects.

It is clear from the work that a standard method for evaluating losses due to ice is needed. The main guidelines should contain a method of how to form the reference output (i.e. the ice free production) and definitions of what to consider as losses due to ice, which is handled in the proposed standard. In addition information about how to handle overlapping ice events and how to take the operation of a de- or anti-icing system into account when calculating the losses needs to be included.

C. 7.2 Future Work

Most important in order to evaluate the performance of the systems is to study a longer time period, so that different icing conditions are included and a more acceptable statistical basis is given. In addition more information about the operation of the systems needs to be known to evaluate the systems, in particular knowledge about signals for when the systems are activated, in operation and measurements of the energy required to run the systems is needed. It is also important to study the production during the summer months in order to gain knowledge about normal occurring variations in output, both within the evaluated wind farms and in relation to the reference wind farms.

It would also be recommended, if possible, to do evaluations where the de- or anti-icing systems of some WTGs within the studied wind farms are turned off during known time periods. This would result in better references, than the reference wind farms used in this work, and therefore give a better and more accurate estimation of the efficiency. It would also be advantageous to study known ice events, not only identified by deviations in the power curve.

Suggested studies would then be to evaluate in which conditions the systems are able to remove ice and when they are profitable to run, and which improvements that can be made regarding starts of the system, the duration of the de-icing cycles and if the power of the system, in particular in Wind Farm 3, could be improved.

The MATLAB-code created to estimate the losses had some flaws that would have to be improved if used in further studies. First of all using another smoothing function is advisable since the power curves and percentiles tended to be underestimated. It would be beneficial to see evaluations of the approach of using P10 and P90 compared to other statistical measurements and also the impact of evaluating all months together, since by evaluating the months separately there will always exist a P10 and P90, even during summer months, and ice events probably risk to be under- or overestimated in years with much or little ice respectively.

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References

[1] IEA Task 19 - Wind energy in cold climates, "Standardized method to assess production losses due to icing from wind turbine SCADA data (T19IceLossMethod)", IEA Wind (rev 0.5), 2014