Shedding of in-cloud icing

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***Abstract*— Ice shedding is an important factor to consider when modeling in-cloud icing, especially in areas characterized by frequent or extreme ice accumulation, and where the temperature is below freezing during long periods. Ice accretion models combined with high-resolution numerical weather data (e.g. from the WRF-model) data are used more and more in evaluating extreme ice loading on transmission lines. Assumptions made on ice shedding in such models may play a vital role when estimating a reliable maximum ice load.**

Keywords— ***Ice shedding, icing model, in-cloud icing, mechanical ice break, melting, extreme ice load***

I. INTRODUCTION

The complete icing process on an overhead conductor can typically be divided into four periods: ice formation, growth, maintenance, and shedding. The shedding process is the topic of this paper, which includes the analysis of shedding from field measurements taken from test spans and from operational 400 kV power lines. Ice shedding is an important factor when modelling in-cloud icing, especially in areas characterized by extreme and frequent icing conditions and where the temperature is on average near or below freezing. The measuring sites used in the study are characterized by frequent in-cloud icing and wet-snow amounts are presumably minimal. The measuring sites are evaluated to have on average a 50-year ice load of 200 N/m and 600 N/m as a maximum. Fig. 1 shows an example from one of the measuring sites where two ice shedding events reduced the overall ice loading considerably. The 50-year ice load had previously been evaluated as ca 310 N/m, based on 19 years of measurements. It would have been exceeded greatly without the ice shedding.

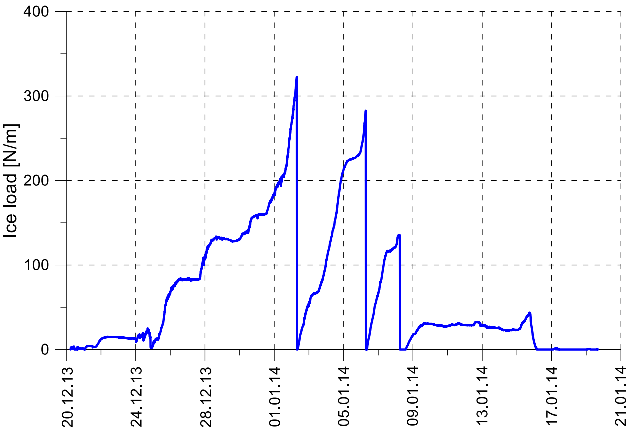

Fig. 1 Measured icing in test site 83-1-A. Two ice shedding events, each larger than 25 kg/m, reduced the potential extreme loading greatly.

The main factors in the ice shedding process are: (i) sublimation, (ii) melting and (iii) mechanical ice break.

The rate of ice loss is low during sublimation, but the process may last days to weeks, leading to marked weight reduction. Melting is an important process in weakening adhesive and cohesive forces in the ice, but it is generally accepted that ice melt models can severely underestimate the intensity of ice loss processes if mechanical ice break is not included.

Some attempts have been made to model the shedding of rime ice, but no widely accepted model exists that has been validated with enough field data. Sundin and Makkonen [1] modelled total ice removal when the air temperature exceeded 0°C for at least three hours. In [2], some improvement was made by including both temperature and wind speed in the shedding model to speed up the ice shedding rate and to allow it to start below zero.

In [3], the ice shedding was modelled as total shedding if the sum of positive temperatures within a day on three consecutive days is more than 3°C.

Hartsveit [4] introduced an ice melting model for ice shedding with the three most important terms as: sensible heat, latent heat and the net radiation term. Observations from Gamlemsvete illustrated that the overall ice removal process was around 10 times faster than indicated with the ice melt model.

Druez [5] studied eleven shedding events from rime accretion from the Mt. Valin icing site. Multiple linear regression analysis indicated that five variables had the greatest impact on the shedding rate (in rank order): normal wind velocity during shedding, the ice mass on the cable at the beginning of shedding, the mean value of air temperature during shedding, the mean value of air temperature during accretion, and the mean value of normal wind velocity during accretion. The study indicated that the shedding rate seemed to be related more to the aerodynamic forces on the accreted ice, than to variables related to the mechanical strength of the accreted ice.

References [6], [7], [5] mention that the ice shedding rate above 0°C is typically about 3 N/m/h, but it may exceed 10 N/m/h in some cases. Field measurements presented in this paper show values far above these values.

The aim of the paper is to present field measurements of ice shedding, primarily the mechanical loss or ice fall, and reveal the complexity that is associated with the modelling of the ice shedding process. Further studies will be made using the data, to improve and validate ice shedding models.

II. DATASET FOR ICE SHEDDING ANALYSIS

Iceland has an extensive network of nearly 60 operational test spans at more than 40 locations, measuring ice accretion in real-time. This study uses data from 28 test spans, with their locations shown in Fig. 4, as well as data from two operational OHTLs. In short, a test span consists of two poles with a conductor strung between them, in which the tension is measured with a load cell. The spans are standardized: the conductors are 80 m long and strung on poles 10 m above ground, using backstays. The most commonly used conductor is 28 mm in diameter (AAAC), but 18 mm conductor (AAAC) is used at few locations. A detailed description of the test setup is given in [8].

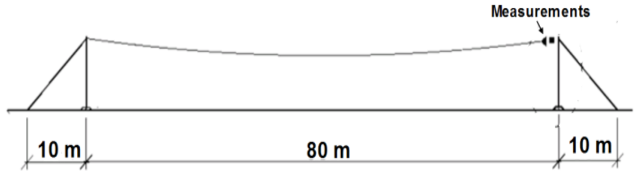

Fig. 2 Sketch of a test span.

Fig. 3 Photo taken along the measuring wire in test span. It shows an old mechanical device, but not the newer load cell type used in this study.

Load cells measure tension at 0.5-1 Hz and store maximum, minimum and average values with a 10 minute temporal resolution. Measurements of the conductor’s end tension are taken. They are then converted into external load per unit length, using the geometry of the test span and mechanical properties of the cable and guy-wires. The underlying assumption is that loading is equally distributed along the span. Information on the wind-speed (measured or simulated, e.g. with WRF) is needed for splitting the unit loading into the transversal (wind) and the vertical load components (ice).

Three different dataset are used in this study:

- From a collection of test spans, for the winter 2013-2014 (previously described in [2])
- From test site 83-1 (Hallormsstadahals), for the period 1997-2016
- From operational 400 kV OHTL FL3 and FL4 from 2006-2019

A. *Dataset from test spans during winter 2013-2014*

This dataset includes 28 test spans, in Northwest- and Northeast-Iceland (locations in Fig. 4), from the winter of 2013-2014. The winter was characterized by extensive and more or less continuous ice accretion for 99 days, from December to March in North- and East-Iceland, with two intense accretion periods from mid-December to mid-January, and again in February to early March. Several overhead structures were damaged during this period, e.g. communication towers. The maximum in-cloud ice load measured during the winter in a test span was 47 kg/m, the greatest total accumulation in a span during the period was 177 kg/m/winter and the total accumulation at the 28 test spans was 1076 kg/m/winter. The ice accretion was chiefly due to in-cloud icing. The atmospheric and icing conditions are described in detail in [2].

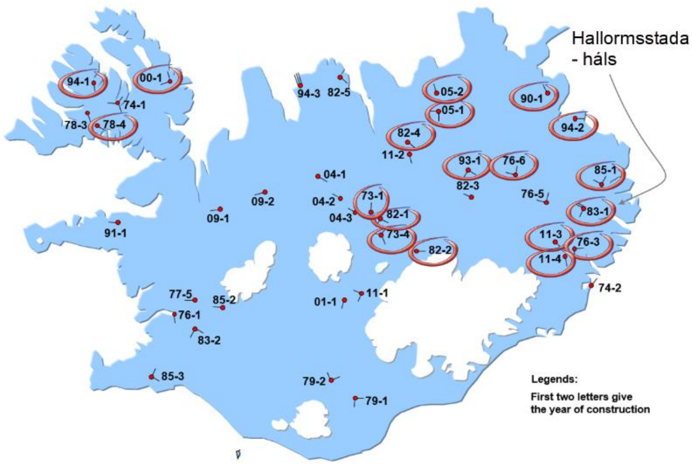

Fig. 4 Locations of test spans in Iceland. Spans in dataset from winter 2013-2014 are marked with circle.

B. *Dataset from test spans at Hallormsstadahals 1997-2016*

Measurements in test spans at Hallormstadahals started in 1983 and have been continuous since. There are three test spans at Hallormsstadahals: 83-1-A and 83-1-C are parallel and are used to compare icing on different conductors. 83-1-B is orthogonal to them. The measuring site is located on a northward sloping, north-south oriented ridge, 575 m above sea level, and in-cloud icing occurs frequently every year during north- and northeasterly flow. A description of the measuring site and measurements is given in [9] and [10]. An automatic weather station with an unheated anemometer is operated at Hallormsstadahals, but the anemometer is typically unreliable during icing events.

C. *Dataset from the operational 400 kV OHTL FL3 and FL4 at Hallormsstadahals*

Two parallel 400 kV OHTLs were built over Hallormsstadahals in 2006 and they have been equipped with load cells and a video camera from the start. FL3 and FL4 are extremely important lines in Iceland, and a simultaneous outage of both lines is not acceptable. Due to their importance, and in order reduce potential icing outages of both lines, one of the line is built with a simplex conductor in this area and the other with a duplex conductor. Fig. 5 shows the location of FL3 and FL4 in relation to test site 83-1. Table I shows further information on the setup at Hallormsstadahals.

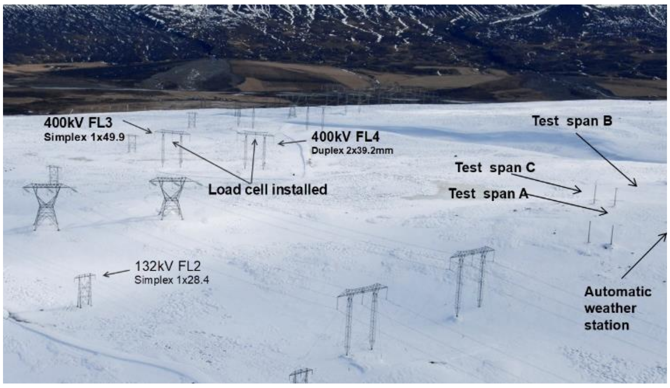

Fig. 5 The measuring site at Hallormsstadahals. Test spans 83-1-A, 83-1-B, 83-1-C and 400 kV FL3 and FL4.

TABLE I
MEASUREMENTS MADE AT HALLORMSSTADAHALS

Meas.	Height a.s.l. [m]	Height above ground [m]	Span length [m]	Direct. perp. to span [°] (true)	Dist. to test span [m]	Cond. diam. [mm]
83-1A	575	10	80	120	-	28.1
83-1B	575	10	80	30	-	28.1
83-1C	575	10	80	120	-	Varies
400kV FL3	540	19	205 & 192	117	325	1x49.9
400kV FL4	545	19	175 & 192	117	272	2x39.2

The annual temperature variation is important when analysing ice shedding, as it reveals the potential for accreted ice to remain for a long time on the spans. Fig. 6 shows the temperature profile for the test span 83-1 at Hallormsstadahals, based on temperature measurements in the period 1997-2016.

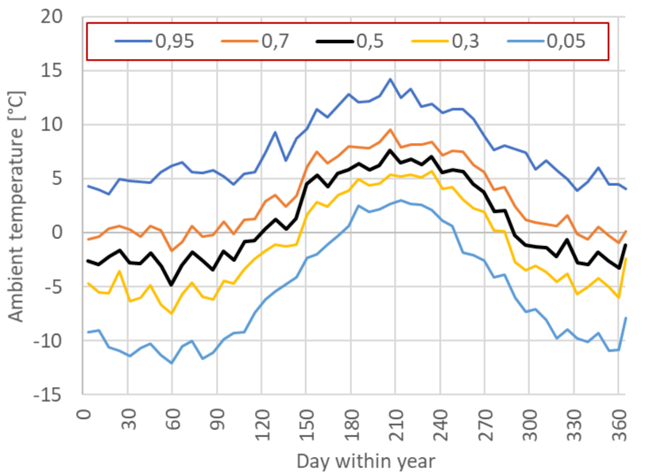

Fig. 6 Measured annual temperature variation at site 83-1 (Hallormsstadahals) in the period 1997-2016. Temperature is given for different exceedance probability: 95%, 70%, 50%, 30% and 5%.

D. *Identification and definition of ice shedding*

Ice shedding was analysed based on a dataset with measurements with a 10 minute resolution. The aim of the study was to focus on the main ice weight reduction in each event, therefore, the identification of sublimation and slow ice melting is not of primary interesse. Following algorithm was used to define ice shedding:

- To start ice shedding weight shall initially be reduced ≥ 0.5 N/m per 10-minute timestep.
- Ice shedding is ongoing while there is a weight reduction during each 10, 30 or 60 minutes step.
- Ice shedding ends when the requirement above is not fulfilled.
- To be defined as an ice shedding event, the total weight reduction must be ≥ 10 N/m and the relative ice reduction must be > 10% of the ice load before shedding.

All shedding events were plotted and visually confirmed, with some events judged unreliable and hence discarded. The algorithm generally identifies correctly the main shedding part that occurs at the end of the event, but sublimation and slow ice melting is not as well identified. If the intention was to capture the initial stage of slow shedding, then a lower initial start value (<0.5N/10min) should be used combined with a minimum hourly shedding rate. In some cases of shedding, the accreted ice is not completely removed before next accumulation starts; in such cases multiple shedding events are recorded.

Fig. 7 shows examples of how each ice shedding event was identified and Fig. 8 show example of multiple shedding within one icing event.

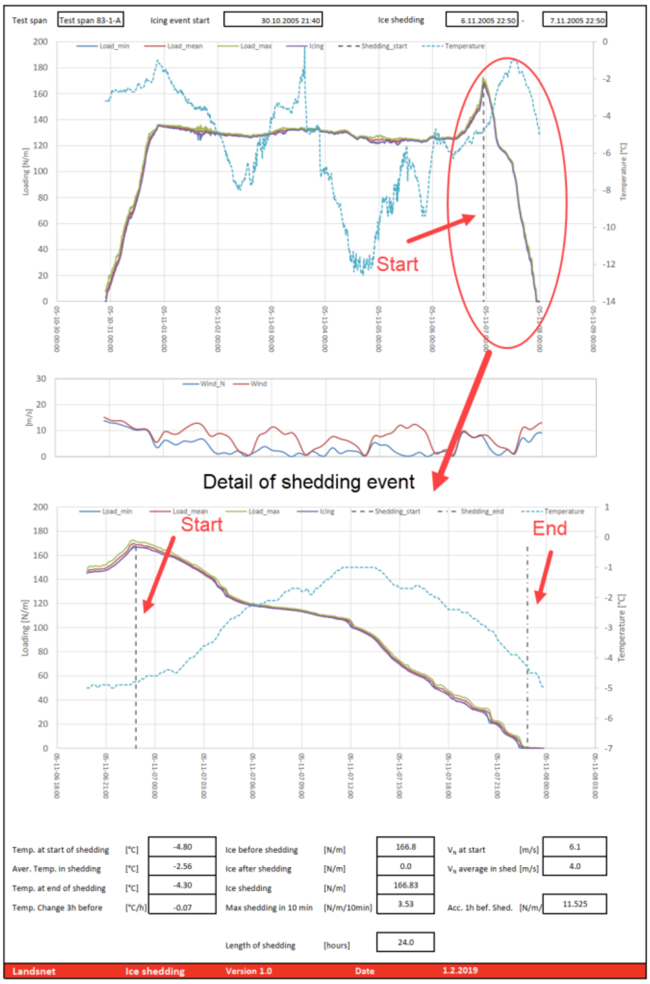

Fig. 7 Ice shedding at test span 83-1, 06-07 Nov.2005. Ice load 167 N/m before shedding. Total ice removal in 24 hours. Temperature: -4.8°C in the beginning, -2.6°C average. Max shedding rate 3.53N/m/10min. Normal wind 6.1 m/s at start.

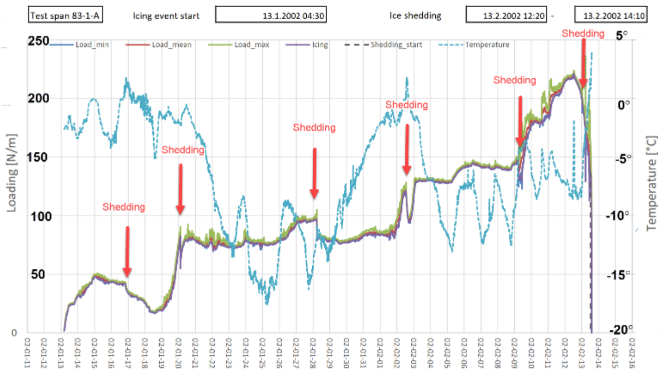

Fig. 8 Ice shedding at test span 83-1. Icing event from 13 Jan.-13 Feb. 2002. Few partial shedding events with some accumulation in between, before final shedding occurs. Algorithm identifies different shedding events here.

Table II show the dataset used in the study, which period is covered, and the number of shedding events identified.

TABLE II
NUMBER OF SHEDDING EVENTS IN DATASETS

Dataset	Period	Nof. Shedding events
Winter 13-14	2013-2014	177
83-1A	1997-2016	304
83-1B	2003-2016	101
83-1C	1997-2016	297
400kV FL3	2006-2019	164
400kV FL4	2006-2019	148

It should be noted that 89% of shedding events are from the spans at the site at Hallormsstadahals. Hence, the results presented here may be strongly dependent on the local weather conditions at the site as well as the span characteristics..

III. ANALYSIS OF ICE SHEDDING

The size of the ice shedding events varies greatly in the datasets as Fig. 9 shows. No event is defined below 10 N/m since it is the lower bound of how ice shedding event is defined in the study. Half of the events are above 21 N/m, 16% are above 50 N/m, 13 % are above 100 N/m and the maximum value is 461 N/m.

There is some uncertainty regarding the two most extreme cases (461 N/m and 451 N/m), as the loading was above the calibration range of the measuring unit, thus these values are the lower bound of the loading.

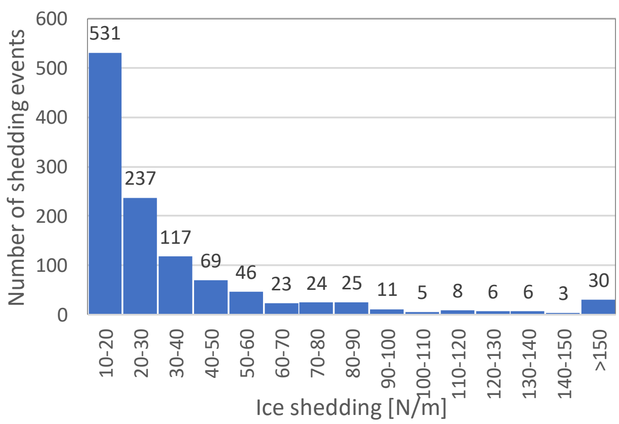

Fig. 9 Distribution of all ice shedding events in the datasets.

Fig. 10 shows the evaluated time length of shedding events in the test spans. 44% of the events occur within one hour and in fact a large part of the shedding occurs within a 10 minutes interval.

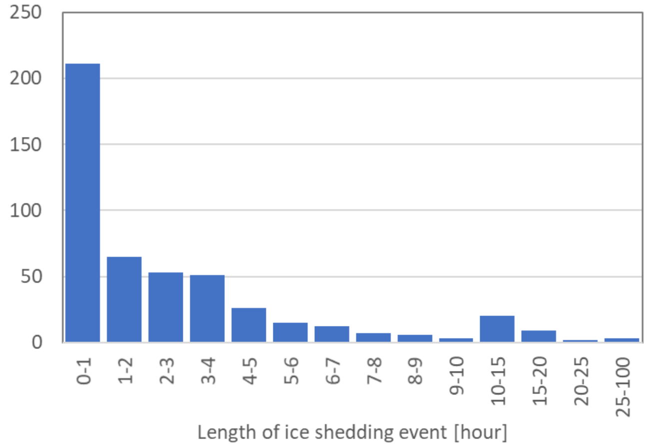

Fig. 10 Time length of main ice shedding events. Sublimation and slow melting part is not included.

Fig. 11 shows the max ice shedding within a 10-minute timestep, as a ratio of the overall shedding in each event. 66 % of all events have more than 90 % of the weight reduction within one 10-minute timestep. Most of the large events with >100 N/m weight reduction have also a large maximum shedding within one timestep.

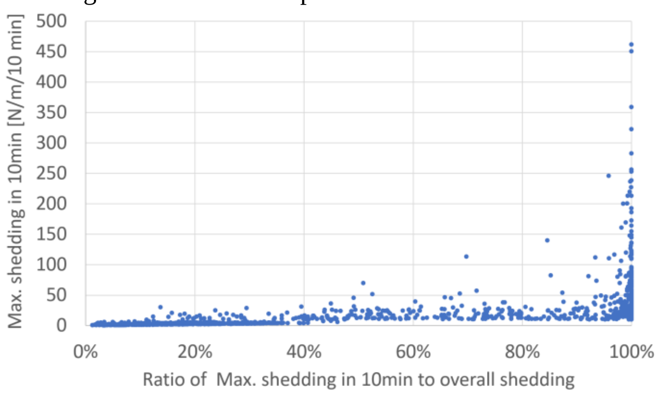

Fig. 11 Maximum shedding within a 10-minute timestep, relative to overall shedding.

Most of the ice shedding events occur within a few days from the peak loading. Fig. 12 shows the number of days from peak loading until end of shedding.

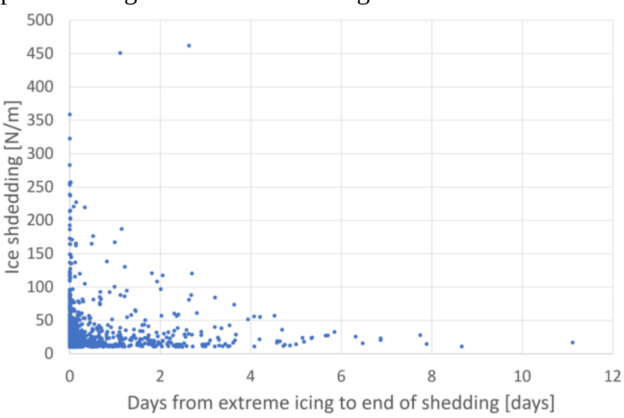

Fig. 12 Time diff. from peak ice load to end of shedding. Peak ice is counted from end of last shedding event if it was not a total ice removal.

A. *Effect of temperature on ice-shedding*

Temperature is one of the main factors influencing the frequency of ice shedding. Fig. 13 shows the distribution of ice shedding events in relation to the average temperature during the event. Fig. 14 shows the relation between amount of ice shedding and average temperature in each event. It is to be noted that 82% of ice shedding occurs below 0°C and 41%% of events are below -2°C. It is not clear whether this is to some extent related to the typical synoptic development during and after an icing event. That is, accretion of rime ice in North- and East-Iceland often starts during easterly or northeasterly flow, which then typically becomes more northerly and colder.

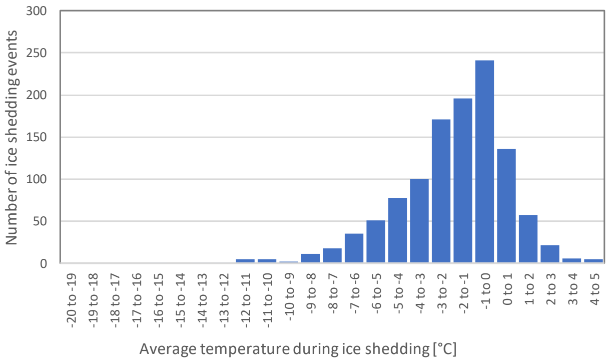

Fig. 13 Distribution of shedding events in relation to average ambient temperature during the shedding.

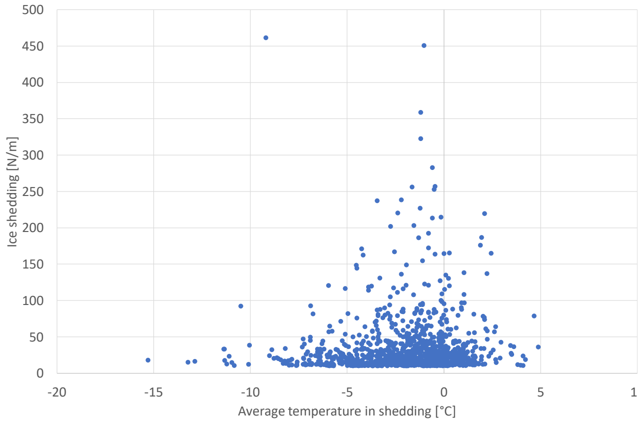

Fig. 14 Ice shedding and average temperature in each event.

B. *Effect of wind velocity on ice-shedding*

It is widely accepted that wind contributes to the mechanical breakage of ice, partly due to static loading and due to risk of galloping and dynamical loading.

Influence of strong wind can be seen in the analysis since the fluctuation in measurements increases, (max., min. and average values is recorded for each timestep). Galloping events are also quite well identified in the measurements. Strong wind is sometimes found to contribute to ice shedding.

Wind speed measurements are made at or nearby a few test sites. However, the anemometers are not heated and thus unreliable during icing events. Wind velocity has been evaluated at each site using simulated wind data from the WRF model. Fig. 15 shows the normal wind component, evaluated with WRF, compared to the overall ice shedding in each event. Fig. 16 shows the evaluated normal wind to average temperature in each event. Both figures show considerably scatter in data and linear correlation is low in both cases.

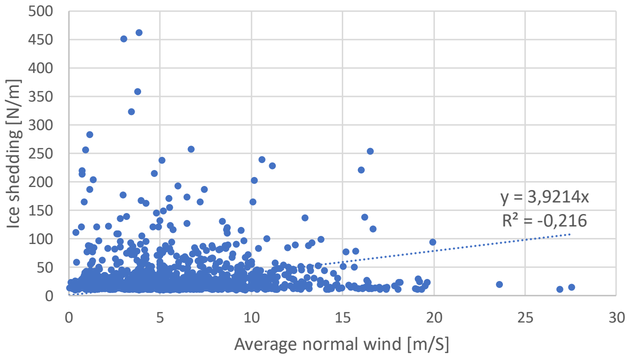

Fig. 15 Size of shedding events in relation to estimated (WRF) average normal wind during the event.

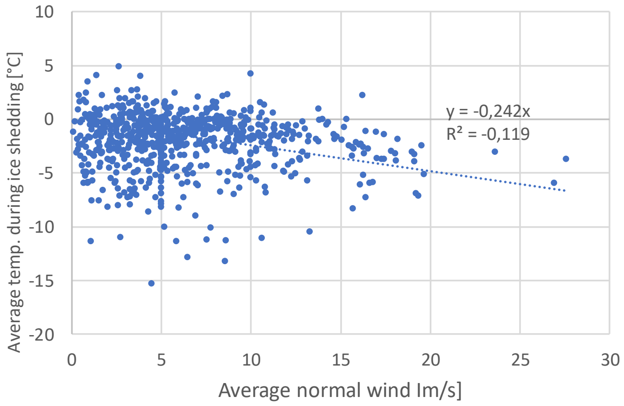

Fig. 16 Average temperature in shedding events in relation to estimated (WRF) average normal wind during the event.

It is believed that influence of wind on shedding is greater than showed here using wind estimated with WRF, since measurements often show fluctuation shortly before shedding. Effect of wind needs to be investigated further.

C. *Effect of net radiation on ice-shedding*

Net radiation influences the thermal balance and the melting of the ice cover, and it can participate in weakening adhesive and cohesive forces in the ice. Reliable data of shortwave and longwave radiation were not available in the study, thus detailed analysis was not made on effects of net radiation on the shedding process. Fig. 17 and Fig. 18 show when ice shedding process starts within the year and at which hour within the day. Large shedding events are occurring in December and January when short wave radiation is very small. Thus, it can be argued that short wave radiation may not be big influence factor in the shedding process in this dataset. It should though be noted that many events are occurring at sites where the temperature is rarely below zero for extended periods. Therefore, the influence of short-wave radiation may be different at sites with long periods with temperature below zero. Furthermore, we note that the influence of the wind and temperature at the time of shedding is not accounted for.

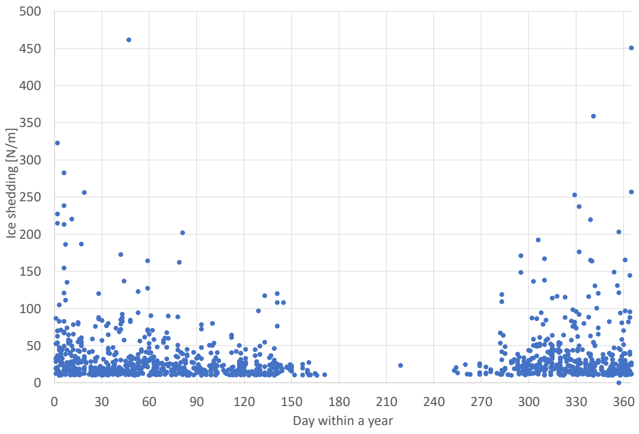

Fig. 17 Occurrence of ice shedding within a year, based on starting day of ice shedding in test spans.

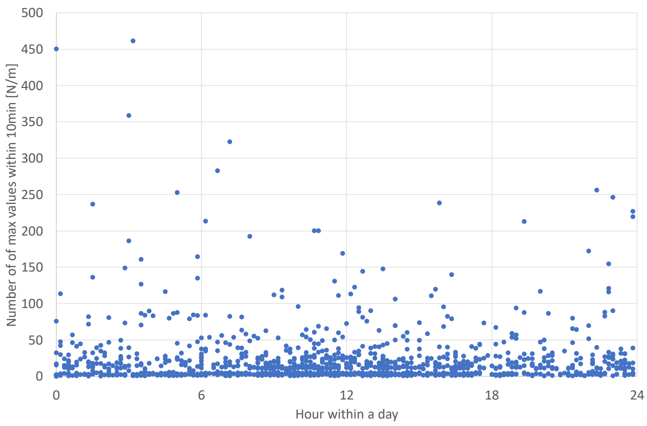

Fig. 18 Occurrence of ice shedding within a day, based on starting time of ice shedding in test spans

D. *Shedding events > 100 N/m*

There are 58 events with shedding above 100 N/m and they are from 11 measuring spans with 5 of them located at Hallormsstadahals. Six of the events are from the 400 kV FL3 and FL4, and 52 are from test spans.

In most of the cases large part of the ice shedding occurs within one timestep in measurement, i.e. within 10-minute interval, in 74% cases the shedding was above 90% in one timestep. This can be observed in Fig. 11. One possible explanation of the large sudden shedding in cases of high loading is related to the amount of static energy that is released, and which can lead to cascading effects on the ice shedding. Average temperature during these events is -1.5°C.

E. *Stochastic nature of ice-shedding*

There are several ice shedding events in the dataset where it is difficult to explain what the root cause of the ice shedding is and what is the triggering factor. It is especially obvious in measurements at Hallormsstadahals where the five measurement units often show quite different shedding. One such event is shown in Fig. 19. The ice shedding process is different, and it strongly influences the peak loading. 400 kV FL3 and FL4 have more shedding events and get less extreme loading than test spans A and C that have same direction.

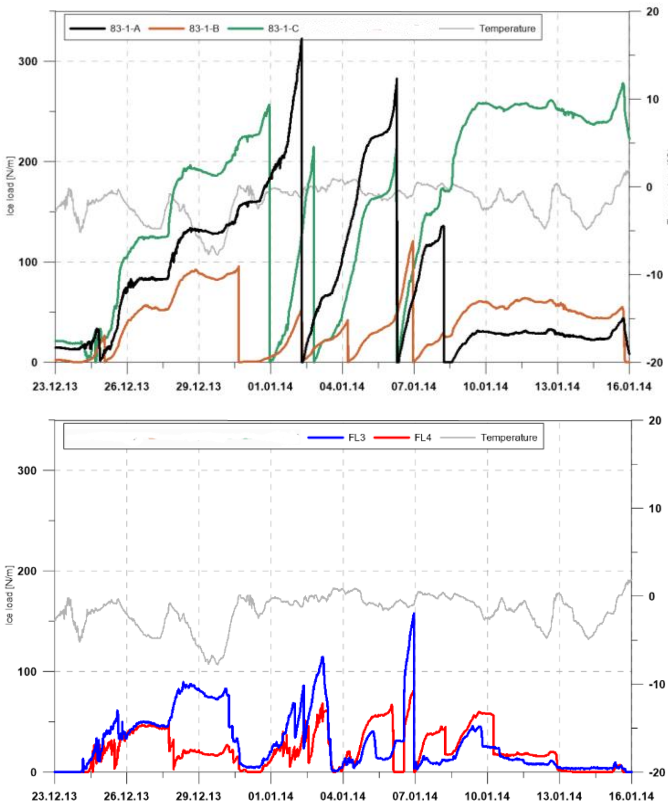

Fig. 19 Icing at Hallormsstadahals 20.12.2013-21.01.2014. Test spans are shown above and 400 kV FL3 and FL4 below. Marked differences are in the ice shedding, which leads to very different extreme ice loading.

Some aspects which can be related to the differences in shedding include:

- Operational, OHTL can, due to joule warming, have different shedding compared to the cold wire in a test span.
- Test span with tension attachment in both ends has different dynamical properties compared to suspension attachment in OHTL.
- FL3 has simplex conductor while FL4 has duplex conductor.
- Direction of 83-1-B is orthogonal to others.
- Different conductor size is used.
- Local conditions at 400 kV FL3 & FL4 are slightly different than at the test spans.

Random effects seem also to be involved and may have considerable influence in many cases. It is perhaps most obvious when comparing data from test spans 83-1-A and 83-1-C when they were installed with identical setup, i.e. 28mm conductor in the period July 1999-Sept. 2007. Fig. 20 to Fig. 22 shows some examples of how ice shedding can be different even though the setup is identical, leading to large differences in the loads. This is not totally surprising as experience has shown that icing does not fall of all conductors in OHTL at the same time.

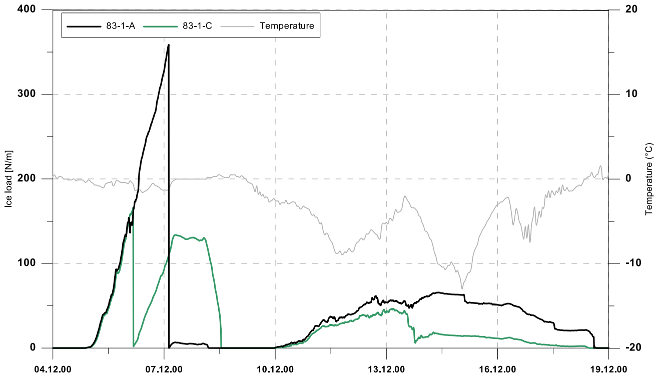

Fig. 20 Icing event 04-19 Dec. 2000 in test spans 83-1-A and 83-1-C. Ice shedding occurs before in 83-1-C and it leads to less peak ice load.

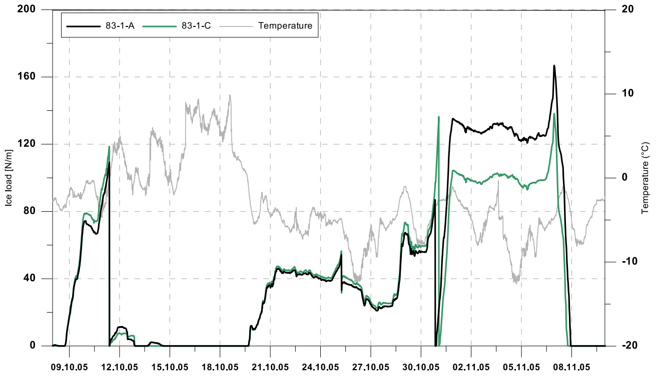

Fig. 21. Icing events 08 Oct. – 08 Nov. 2005 in test spans 83-1-A and 83-1-C. Overall good correlation between ice shedding.

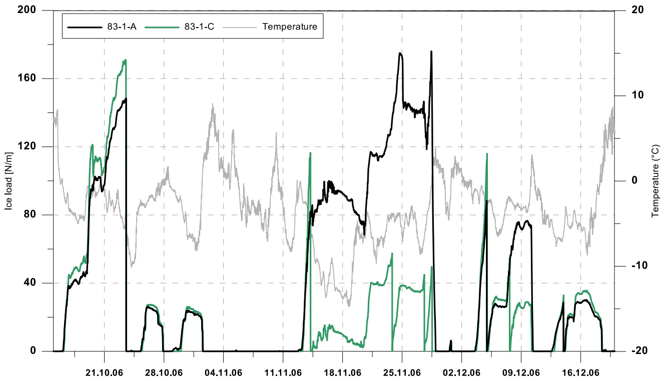

Fig. 22 Icing events 15 Oct. - 20 Dec. 2006 in test spans 83-1-A and 83-1-C. Ice shedding in some cases occurring at same time but in other cases not, e.g. 14 Nov. Here 83-1-C has tendency to shed before 83-1-A.

F. *Simplex – duplex in operational OHTL*

It has been argued and shown with numerical models that a simplex conductor gets more ice accumulation than each sub-conductor in a bundle, due the increased rotational stiffness of the bundle, if the conductors are interconnected with spacers. Another influencing factor is the ice shape that tends to be more wing shaped in the bundle and more prone to ice shedding. Fig. 23 shows an example of wing shaped icing in a duplex conductor at Hallormsstadahals.

Due to the great importance of the 400 kV OTHL FL3 and FL4, linemen monitor the icing conditions and are prepared for ice removal action when needed. Their experience is that a notable difference is in the shedding process between the lines, and that FL4 (duplex) usually sheds icing before the simplex in FL3. Ice shedding events in the measurements confirm that there is a marked difference between the lines and that ice shedding begins on average at lower load intensities and is more frequent on the duplex line than in the simplex line. Consequently, there are more large ice shedding events in the simplex line and it has 14 out of 20 highest shedding events. Fig. 19 and Fig. 24 show some of the most extreme measured ice loading in FL3 and FL4, and how ice shedding and accumulation behaves differently. The simplex line has typically a greater ice load but in the event from March 2010 it is the duplex that gets a higher loading.

Fig. 23 In-cloud icing on duplex conductor in FL4, Dec. 2006.

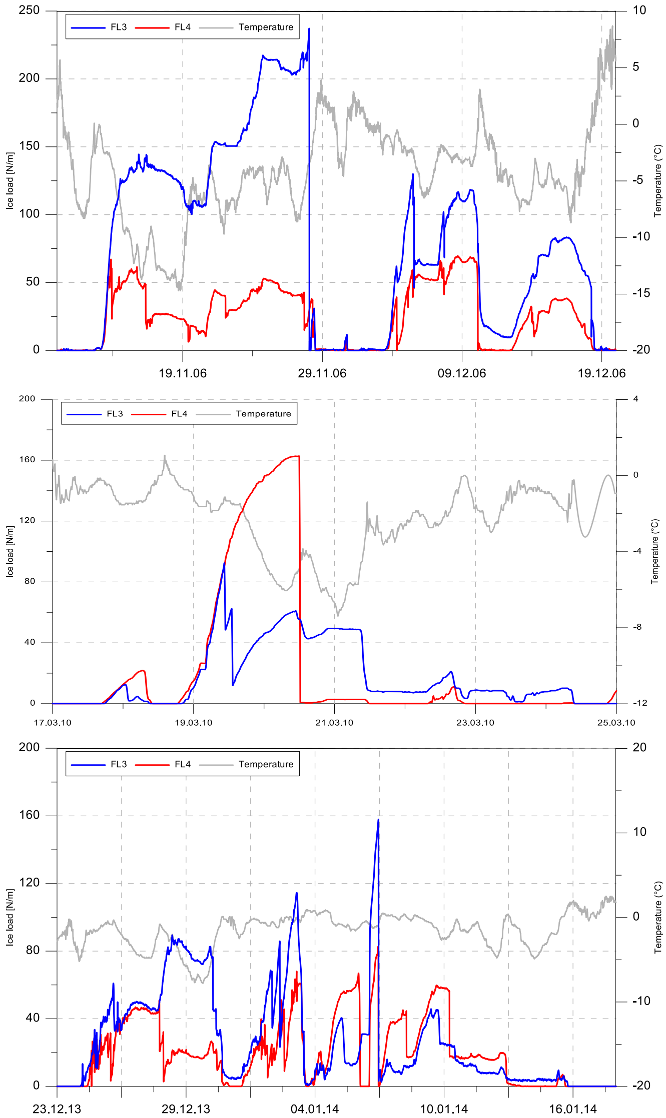

Fig. 24 Some of the most extreme measured ice loading in FL3 and FL4. The duplex in FL4 has more tendency to shed icing before the simplex in FL3. The event from 2010 is though different.

IV. Summary and Conclusions

This study focuses on ice shedding in a large observational dataset from test spans and operational OHTL in Iceland. It is unique with respect to the amount and detail of the observational data, as well as it also contains data allowing for the comparison between different line setups such as: • simplex vs. duplex, • different conductor sizes, •same conductor in identical parallel spans (i.e. variability in random effects), and •·test span versus operating transmission line. Main focus is on mechanical ice fall and limited focus is on the slow sublimation and melting processes. The analysis of shedding events in this large dataset indicate that studies limited to small datasets may give misleading results due to the complex and stochastic nature of the shedding. Majority of the shedding events studied here (89%) are from five spans on one site, thus the local weather conditions at the site could have a significant impact on the results.

The study presents the general statistic from the ice shedding events that have been identified. The results can be used as an input into improvement of ice shedding models, as well as indicators of which aspects of the shedding processes and the observational data need a more detailed investigation. The following conclusions can be drawn from the study:

- Ice shedding can have big impact on extreme in-cloud icing. It is a complex process and has a stochastic nature.
- Most shedding processes occurred in a temperature range of -3 to +1 °C.
- Large ice loading most often breaks completely off in a short time. There is a very strong tendency that a large shedding events take place within a single 10-minute measuring step. Especially when the shedding event is >50 N/m. 58 events had shedding above 100 N/m and 43 of them (74%) had load reduction above 90% of the loading in a single 10-minute measuring step.
- Sublimation and slow melting in this dataset contribute to little ice removal compared to mechanical ice break.
- Shedding in a duplex conductor begin on average at lower load intensities than in a simplex conductor. Consequently, there are more large ice shedding events in the simplex line

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