Development of a 50-year return value ice load map for Sweden

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Abstract— **This paper describes the development of an ice load map of Sweden based on simulations from a state-of-the-art numerical weather prediction model. Ice loads due to both wet snow and rime ice have been calculated with return periods of 50 years. Historical failure reports from Svenska kraftnät's archive have been investigated systematically and icing events documented with sufficient details have been used for model validation. The new icing map is intended for use in future planning and mechanical design of overhead power transmission lines in Sweden.**

Keywords— ***Wet snow, rime icing, 50 year return period, WRF***

I. Introduction

The Swedish transmission system operator, Svenska kraftnät, is currently revising the ice load values used in the design of the transmission grid in Sweden. As a first step, the current study has been initiated in order to generate an icing map showing the regional variation in the expected extreme ice loads, i.e. the ice load/ice thickness with a return period of 50 years. As in most countries, the availability of widespread direct icing measurements is poor, and limited information is available on the regional and local variation of ice loads. Therefore, the current study investigates the feasibility of producing, from a practical point of view, a useful icing map based on a large dataset of simulated meteorological data generated with a state-of-the-art numerical weather prediction model. Old reports from historical icing events (failures or observations) have been provided by SVK for comparison with the model results.

Even though the number of documented icing related failures generally is small, there are some examples where the observed ice load is significantly exceeding the design load, even several times during the last few decades. Furthermore, the small number of failures may indicate that at least in some areas, the actual reliability of the lines is much higher than the intended reliability from the design phase. By mapping of the expected ice loads, SVK can identify the regional variation in ice loads and furthermore design the lines accordingly.

The scope of the current study is to produce an ice load map showing the large scale regional variation in ice loads in Sweden, not the minor variation on the small scale, i.e. span by span variation. However, since areas exposed to severe rime icing are often limited to peaks of exposed hills and narrow ridges, a separate map (or map layer) with higher resolution is needed. Such a map layer will visualize the local areas where a special consideration is needed with respect to the design ice loads.

II. Observations

Reports documenting icing events on Svenska kraftnät's lines have been investigated systematically, and reported icing events as early as 1921 were found. Among the reports investigated, approximately 10 dated failure reports contain quantitative information about the mass and/or thickness of ice. Fig. 1 shows an example of a well-documented icing event that took place in January 1951, resulting in an ice load exceeding the design value by several hundred %. For the icing events that took place after 1979, the modelled weather data were available for a more detailed investigation. Some general conclusions can be drawn based on the investigation:

- The majority of the incidents were caused by extensive vertical loads occurring during intense snow fall at low wind speed.
- Meteorological measurements as well as modelled weather data confirm that dry snow accretion on already iced conductors represent a significant contribution to the total ice mass in several extreme cases.
- Since 1979 all reported events, except one, occurred in areas exposed to rime icing
- Many events result from a combination of wet snow and dry snow, or rime ice and dry snow.
- Except the report from 1921, all reported icing events were located in northern Sweden.

Fig. 1 Icing report from 19 January 1951. Measured icing diameter of 40 cm and an ice mass of 11 kg/m on one phase conductor.

III. Methods and Data

A. Hindcast data

The atmospheric hindcast data is prepared with the Weather Research and Forecasting (WRF) model. It is a state-of-the-art mesoscale atmospheric model [1] and it has previously been extensively used in icing studies (e.g. [2 - 6]). The model has been run for 1979 – 2018 for a domain covering Norway and Sweden at 4 km grid spacing (Fig. 2) horizontally and with 32 vertical levels. The simulations are initiated and forced on the lateral boundaries by the ECMWF–ERA Interim dataset [7]. The hindcast is composed of 27-hour simulation cycles where the three first and overlapping hours of each cycle are considered as spin-up and therefore deleted. The Thompson microphysics scheme [8] is used for parameterization of the cloud and precipitation processes, and MYJ scheme [9] is used for boundary layer mixing. This resulting dataset is used in the present study to calculate the wet snow loads as well as the extreme wind speeds. A similar simulation at 4 km grid using the FNL [10] data as input has been performed for the time period 2000 – 2018. This dataset is preferred over the aforementioned dataset for analyses of the rime ice loads due to an improved interpolation of temperature and humidity along the coast line and lakes. Both datasets have been generated with the WRF ARW model version 3.2. All data are stored at a 1-hour temporal resolution.

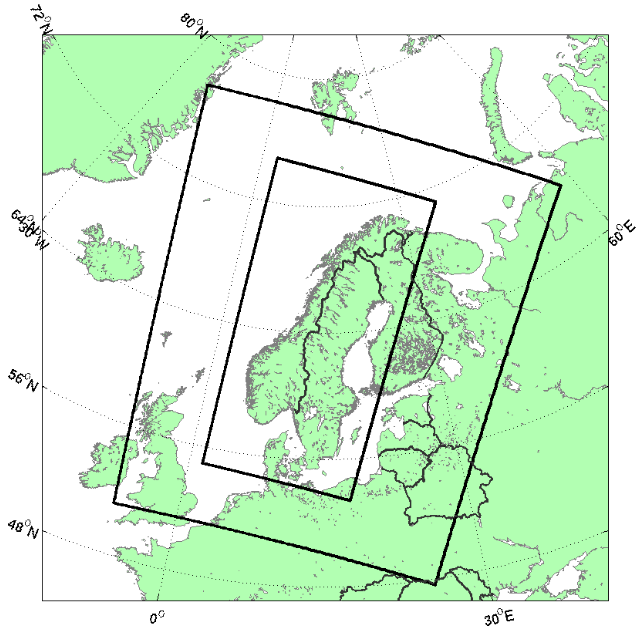

Fig. 2 Model domain set up showing the two nested domains of the WRF simulation. The horizontal grid spacing is 12 km and 4 km respectively for the outer and the innermost domains.

B. Wet snow modelling

Accumulation of wet snow on a horizontal wire can be modelled based on precipitation, wind, temperature and humidity data. The necessary variables are extracted as time series from the hindcast data, and the icing rate is subsequently calculated for each time step. The approach used in this analysis is based on the accumulation model calibrated towards a large number of measurements on Iceland [11], however, a few additions have been made in order to optimize the model with respect to the local observations:

- Complete ice shedding is assumed when the surrounding wet-bulb temperature exceeds 1.5 ˚C.
- Complete ice shedding is assumed if the ice load is present and unchanged for more than 48 hours. In rare occasions the ice may freeze and stick to the conductors for a longer time period, however the local experiences (low density snow accumulation in forest areas) confirm that the ice rarely remains on the wire for an extended period of time, even at temperatures below freezing. Due to wind stress, dynamical breaking and sublimation the accreted snow normally sheds off shortly after an icing event.
- Dry snow is allowed to accumulate on a pre-existing wet snow sleeve at low wind speeds (<5 m/s). However, the accumulated dry snow, typically with low density, is assumed to shed off at wind speeds exceeding 5 m/s. Hence, dry snow does not contribute to the combined load case of wind on iced conductors.

Wet snow events are quite rare in nature, and their occurrences are very sensitive to the ambient conditions. Even with more than 39 years of data there are relatively few events to base the extreme value analysis upon. In order to expand the basis for an extreme value analysis, a post processing ensemble has been constructed. The ensemble consists of 40 different model runs, where the temperature is perturbed within the interval of ± 2 °C from the original model temperature. Extreme value analysis is then performed on each ensemble member and median of the 40 extreme value distributions is used at each model grid points to draw the icing map.

C. Rime ice modelling

Rime ice accretion is calculated based on the time dependent ice accretion model described in [12] and the methodology in [13]. The model includes rime icing (in-cloud) as well as freezing drizzle and freezing rain. The ice load is based on a temporal integration of the hourly icing rate which is calculated based on the simulated atmospheric data described above, which includes information on wind speed and supercooled atmospheric liquid water content.

D. Generation of maps

Since wet snow icing and rime icing are treated separately, the ice loads due to wet snow and rime ice are divided into two separate maps. The wet snow loads represent the highest loads in the majority of Sweden, in particular at the locations of the transmission lines, and therefore, form the basis for the main ice load map. The loads due to rime icing become significant on exposed hills and in mountainous regions. The rime ice map is mainly developed to identify areas where a special consideration is needed with respect to the design ice loads.

The wet snow ice load map has been calculated through the following steps:

1. Time series of wet snow loads have been calculated for each individual grid point in the model domain, for all 40 ensemble members. Ice loads are calculated both for a theoretical rotating line always oriented perpendicular to the wind speed (theoretical maximum ice load) as well as for horizontal lines fixed in four different directions: 0º, 45 º, 90 º and 135 º.
2. At each grid point, an extreme value analysis of maximum wet snow mass has been performed using a peaks-over-threshold (POT) analysis, resulting in estimated 50-year values of wet snow loads for each of the 40 ensemble members for each direction.
3. At each grid point the worst case line orientation has been identified, and the 50-year ice loads are scaled to represent loads on a horizontal power line oriented and fixed in the worst case direction (perpendicular to the predominant icing wind direction)
4. A map for wet snow is drawn based on the median value of the 40 estimated 50-year ice loads for each grid point.

The rime ice load map has been calculated through the following steps:

1. In order to account for sub-grid-scale variation (terrain effects) in rime ice loads the meteorological variables inside each 4 km x 4 km grid box have been spatially interpolated to a 1 km x 1 km grid using a high resolution digital terrain model [14].
2. Time series (18 years) of rime ice loads (on a reference object) are then calculated for each grid point in the 1 km x 1 km grid.
3. At each grid point, an extreme value analysis of maximum rime ice load have been performed by fitting the generalised extreme value distribution (GEV) to the annual maximum rime ice loads.
4. A 1 km x 1 km rime ice map is drawn based on the estimated 50-year values at each grid point.

IV. Results

A. Wet snow map

The wet snow load map presented here shows the results from the analysis without any spatial smoothing or further processing. In order to apply the results in planning and design of power lines, it is assumed that some further processing (e.g. spatial averaging) is needed in order to identify the regional ice load zones rather than the local variation.

The map shown in Fig. 3 is based on the 4 km x 4 km data, however, the results have been re-gridded to a 1 km x 1 km regular grid for practical reasons (i.e. for comparison with the 1 km x 1 km rime ice map). The values range from 20 N/m to 60 N/m for most of Sweden, except from the mountainous regions close to the Norwegian border. There are, however, certain areas with systematically higher loads. Most prominent is the maximum zone located 50 – 100 km inland from the coast line between Sundsvall and Umeå where the wet snow loads reach 60 – 100 N/m.

The snow loads shown in the map represent the maximum snow load independent of wind speed. Hence these should be considered as vertical loads, or ice loads at no wind. In many areas, the wet- and dry snow accumulation only occur in situations with low wind speed, typically in the deep pine forests. In such areas the horizontal forces due to wind on iced conductors is typically insignificant compared to the horizontal forces associated with the extreme wind events without icing.

The wet snow load map in Fig. 3 is calculated for a horizontal conductor with an outer diameter of 3 cm, oriented in the worst case direction, i.e. normal to the predominant icing wind direction. In many areas the ice load can be reduced if the power line is oriented with a large component parallel to the icing wind direction. To benefit from such reductions due to a favourable line direction, a digital map with several layers is required. Alternatively a site specific report could contain such information.

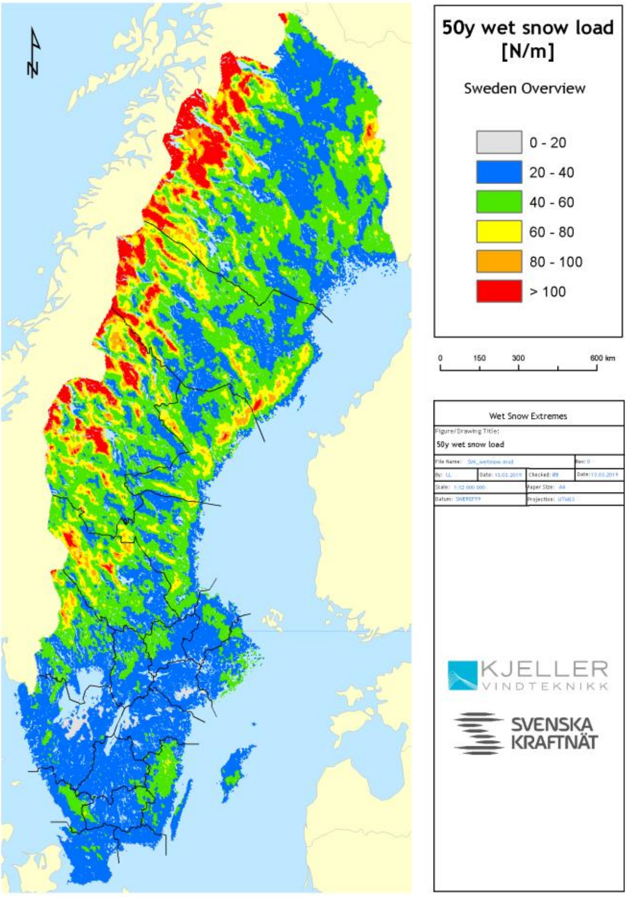

Fig. 3 Map of 50-year wet snow loads. Based 4 km x 4 km, but re-greidded to a 1 km x 1 km grid.

B. Rime ice map

The map shown in Fig. 4 is based on the results of the rime ice analysis at a 1 km x 1 km grid, without any further smoothing or filtering of data. In contrast to wet snow, rime ice is limited to very local and elevated areas. In the highest mountains close to the Norwegian border, the 50-year rime ice loads reach several hundred N/m.

In most regions, the 50-year rime ice loads are much lower than the 50-year wet snow loads, in particular for the typical locations of power lines. However, on exposed hills and in mountainous regions, the rime ice loads become significant. If a new power line is planned through such an area, special considerations should be performed for several reasons:

- Duration. The rime ice may accumulate over a long time period, often several weeks.
- Rime ice has a higher correlation with strong winds than wet snow (except certain coastal areas).
- The rime ice may vary significantly in density and the irregular ice shape typically increases the drag coefficient of the iced conductors.
- The uncertainty of the estimated 50-year loads is large due to the sharp vertical gradient and the long duration (i.e. model errors are accumulated).

From a practical point of view it is therefore recommended to use the modelled rime ice loads to identify the areas associated with a risk of rime icing rather than using the estimated 50-year values directly as design loads. An example of such a risk map is shown in Fig. 5. Here, a grid box is "flagged" as a risk area if the estimated 50-year rime ice load is higher than 50 % of the estimated wet snow load.

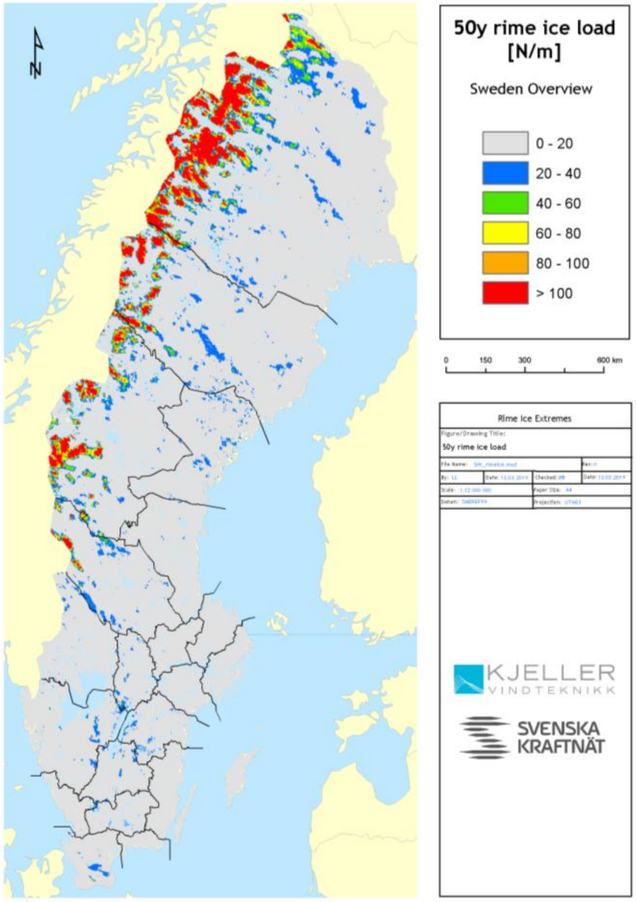

Fig. 4 Map of 50-year rime ice loads on a reference object according to [12].

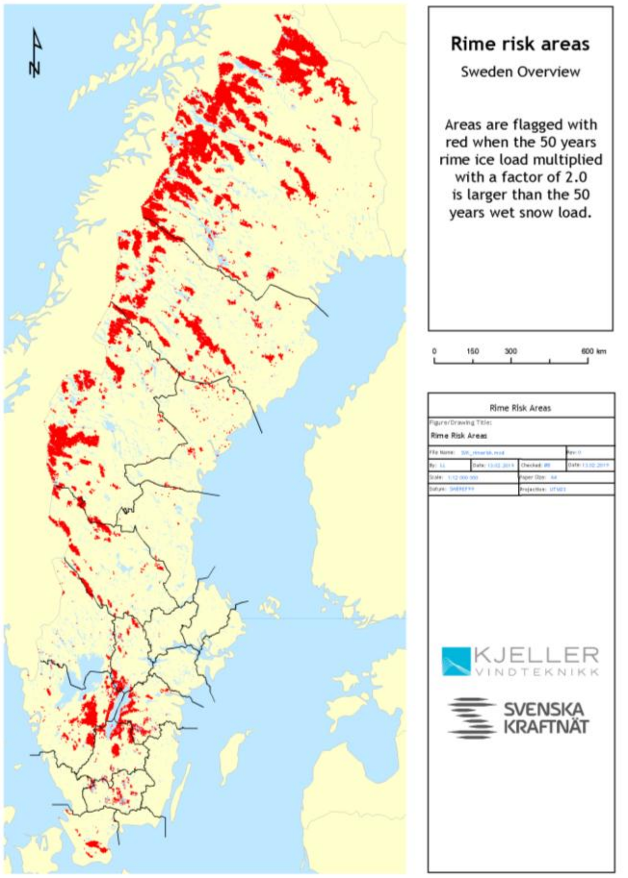

Fig. 5 Example of a risk map, giving the areas where rime ice may be significant.

V. Summary and Conclusions

Even though observational data on actual ice loads is not available for proper verification of the icing maps, the regional distribution, as well as the magnitude of the modelled loads corresponds well with the operational experiences from Svenska kraftnät. However, the icing maps presented here only show the estimated 50-year ice mass, i.e. the vertical load due to ice accumulation on conductors. From a design perspective, data on the expected horizontal forces due to wind on iced conductors is needed. Therefore, as a follow-up to the work presented here, a similar project is launched for mapping the 50-year extreme wind speeds. This study includes mapping of the joint probability of wind and icing. The wind and ice maps as well as appropriate combination factors will be prepared for future design and incorporated in the Swedish NNA, SS-EN 50341-2-18.

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