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An objective approach for selecting ice or wet-snow design loads on transmission lines

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Ice and wet-snow design loads affect the investment costs and the potential maintenance costs for overhead lines more than any other single loading case in most countries exposed to snow and freezing temperatures during winter. The dependence of ice loads on investment costs for both steel towers and wood poles as well as the climatic variations of icing are shown. The paper summarizes the need for such data and refers to IEC recommendations for procedures and measurements of loads, especially as probabilistic methods for design require more comprehensive information on ice accretions on overhead lines, including variations due to conductor configurations. Icing information from icing models based on general meteorological data is summarized, including the potential for future application of atmospheric boundary-layer models as used by weather forecasting centres. A methodology for handling some topographic influences is introduced. The paper concludes with two case studies, one for glaze ice and one for wet-snow loadings.

Keywords: overhead lines; wind and iceloads; models; iceload measurements; probabilistic methods; topography

1. Introduction

In many parts of the world ice loading is the most important single parameter influencing the capital costs and performance of electric overhead lines (see, for example, Fikke *et al.* 1982; Schauer & Hammerschmid 1982). Ice loading is also crucial when upgrading old lines. In particular, information about ice loading is important when the reliability of electrical networks needs to be established. A proper understanding of meteorological load and its application is also important for developing maintenance guidelines for transmission lines.

A survey of published literature shows that there is a significant amount of information available for estimating wind loads for the design of overhead transmission lines. Further information can be found in Ervik & Fikke (1982), McComber *et al.* (1982), Richmond (1982), Goodwin *et al.* (1982), Krishnasamy & Tabatabai (1988), Mallory & Leavengood (1982), Golikova *et al.* (1982), Krishnasamy & Kulendran (1998), Lott & Jones (1998), Poots (1998) and Thorsteins & Eliasson (1998).

However, there is insufficient information available to determine ice, snow or wind-on-iceloads. Even the limited information available is fragmented, and for the most part insufficient to estimate the loads due to ice, snow or wind-on-ice. There is no single source of information to which designers can refer to calculate iceloads on transmission lines. Therefore, a comprehensive set of guidelines will be of immense

Table 1. *Steel weight as a function of design ice loadings from figure 1*

iceload ($N\ m^{-1}$)	steel weight ($t\ km^{-1}$)
50	31
100	52
150	68
200	82

help to engineers and designers. The objective of this paper is to provide guidelines to gather reliable ice data and to discuss the economical consequences of using good and accurate ice data.

This paper attempts to discuss in some detail the following important topics.

(i) Economical consequences of ice loading.

(ii) Uncertainties of loading and return periods.

(iii) Outline of icing processes.

(iv) Sources and availability of icing data.

(v) Recommendations for data gathering.

(vi) Survey of icing models.

(vii) Effects of terrain and ice loading.

(viii) Case studies:

- (a) loads due to glaze ice in Ontario, Canada; and
- (b) wet-snow loads in southern Norway.

2. Economical consequences of ice loading

(*a*) *Relation between investment cost of overhead lines and ice loading*

There are two major factors influencing the marginal costs of electrical overhead lines when the iceload increases, as follows.

(1) First, each tower or mast has to be strengthened in order to support the increased loads from the wires. This leads to the use of heavier steel towers or larger wood poles.

(2) Second, the span length must be reduced to keep the conductor-loading within the design limits. This results in more steel towers or poles per kilometre of line.

Some typical values are given below to illustrate the influence of iceload on steel tower weight.

The relationship between the weight of steel in transmission towers and design iceloads has been established for some typical 300 and 420 kV lines in Norway (Fikke

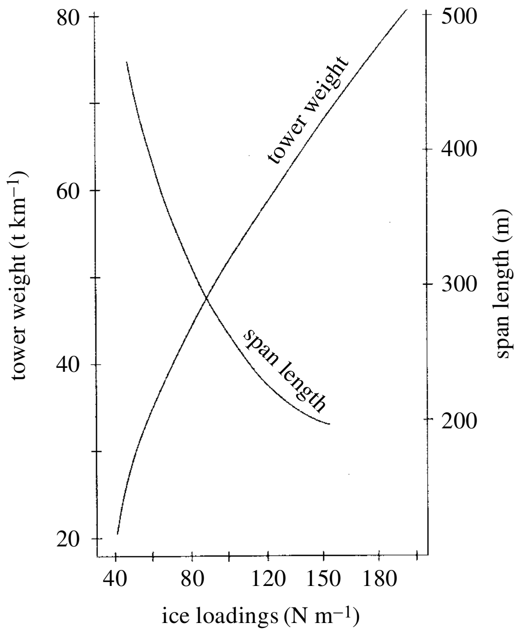

Figure 1. Tower weight and span length as a function of iceload.

et al. 1982). The average span length and weight of steel as functions of iceload is shown in figure 1. It can be seen that when iceload exceeds 5 or 6 kg m^{-1}, the amount of steel per kilometre of line increases rapidly. Some typical values are listed in table 1.

Furthermore, for iceloads of the order of 100 N m^{-1}, a marginal change in iceload of ± 10 N m^{-1} will result in a change of ± 3 t of steel per kilometre of line.

Because the erection costs also generally vary mainly with the amount of steel, the investment costs of a new transmission line mostly depend on the iceload. Other variable costs due to transportation, construction site installations, etc., have, in general, a relatively small effect compared with the cost variations due to the iceload. For example, the costs (in dollars in 1998) of a particular 420 kV single circuit line due to iceload are as follows:

$$\begin{aligned} \text{steel cost and manufacturing} &= 1620 \text{ US\$ t}^{-1} \\ \text{erection cost} &= 1215 \text{ US\$ t}^{-1} \\ \text{total (steel + erection) cost} &= 2835 \text{ US\$ t}^{-1}. \end{aligned}$$

Hence, the marginal cost of a transmission line is at least 8500 US\$ per kilometre for every 10 N m^{-1} of ice loading. If foundation and hardware costs were included, the total cost variations with ice loadings would be even greater.

(*b*) *Relationship between iceload and size of wood-pole structure*

A study in Norway (Jøsok 1992) shows similar dependence on investment costs, except for the right-of-way, from ice loadings for the 22 kV distribution network, which is based on wood poles. Figure 2 shows this dependence for some typical steel–aluminium conductors. This dependence is almost linear and *ca.* 2000–2500 US\$ per

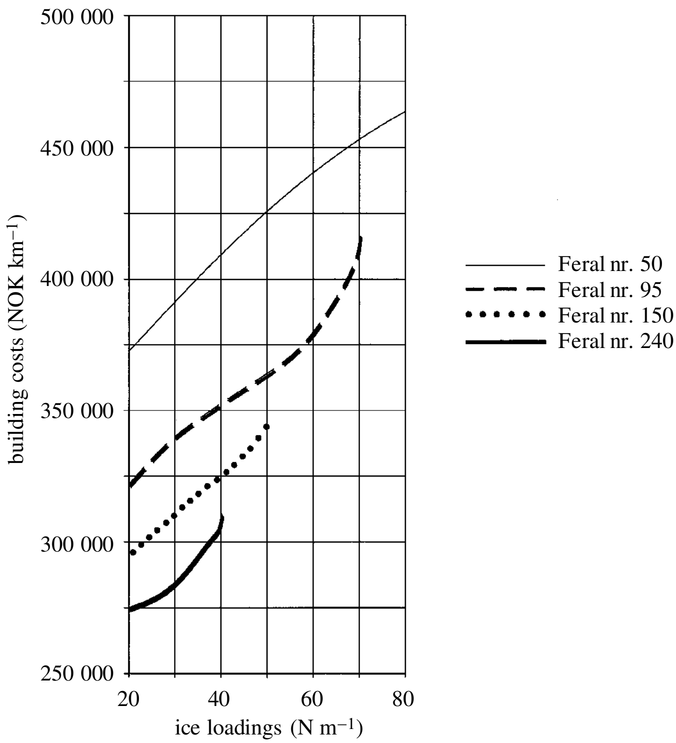

Figure 2. The influence of design ice loadings on the investment cost of 22 kV distribution lines (except right-of-way costs) (after Jøsok (1992)). (NOK, Norwegian Kroner; 100 NOK = 12.82 US$, March 1999.)

kilogram of iceload and per kilometre of line. These curves are based on the new Norwegian standard for mechanical design of power lines, which is, in principle, close to the new standard to be published by CENELEC.

The uncertainty of meteorological loads used in the transmission-line design depends on the accuracy of the data that are used in determining them. This uncertainty will vary with the type of load being considered, i.e. whether it is load due to wind or ice. Often the data used are taken from charts or tables available in building codes and other similar documents. However, the amount and the quality of data used to develop these charts or tables may not be quite adequate in all these cases.

In the case of wind, the extreme wind charts are generally based on data from a group of meteorological measurement stations. However, the spatial variations of wind speeds are relatively high. The uncertainty of an extreme wind speed with 50 year return period will easily be *ca.* $\pm 10\%$, and the uncertainty of the corresponding wind pressure will be $\pm 20\%$, or higher.

In the case of extreme iceload, it is very rare that possible load charts are based on long and reliable time-series of data. An exception to this is Canada, where there have been systematic programmes for collecting iceload data since the 1970s. In general, however, they are determined from data series of limited length, say 5–10 years. The spatial variations of iceloads are also much higher than those of wind speeds. Therefore, it is often likely that the uncertainty in the iceload is in the range of ± 30 to $\pm 50\%$.

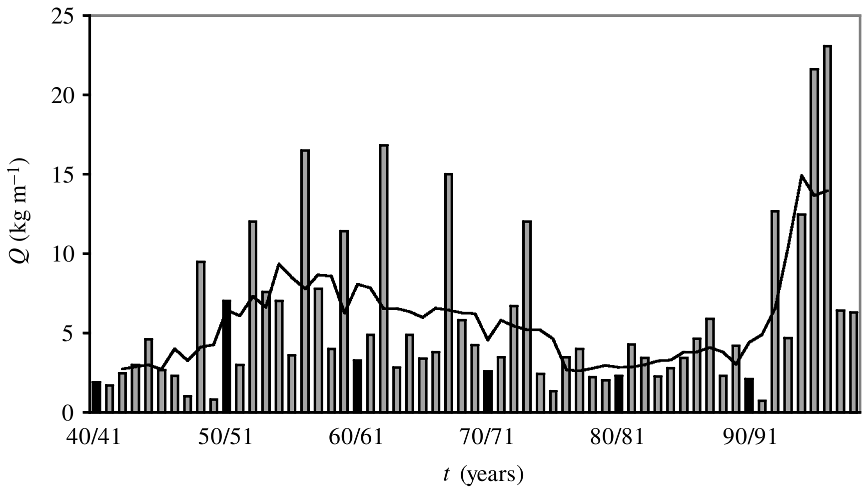

Figure 3. Annual maxima of ice loadings from Studnice (800 m above sea level), the Czech Republic, between 1940 and 1999 (from Popolanský *et al.* (1998), and later updated).

In order to illustrate this, an example is given here from probably the longest series of continuous and homogeneous measurements of ice loadings (presented by Popolanský *et al.* (1998)). These are from the test site Studnice (800 m above sea level) in the Czech Republic. Figure 3 shows the annual maximum load (columns) measured through 59 years on a dedicated stand. The curve represents 5-year running averages of the same values plotted at the central year.

It can clearly be seen that if the design ice-loadings of that area were based on measurements from the 1950s or 1960s, they would be quite different from those using measurements taken in the 1970s or 1980s. Furthermore, it is surely quite important to consider the development of the icing climate in the 1990s. The importance of continued measurements on this site cannot be emphasized strongly enough.

In order to illustrate which costs the uncertainty represents for a 420 kV transmission line, one example is given for Norway based on the information from § 2 *a*. A 40% uncertainty in predicting a design iceload of 15 kg m^{-1} represents an uncertainty of ±20 t of steel per kilometre of line, corresponding to ±55 000–60 000 US$ per kilometre of this transmission line. Hence the uncertainty inherent in the design iceload may represent more than 10% of the total investment cost of a single circuit line (triplex) with horizontal configuration.

As a further illustration of the economic influence of the design iceloads, the results of a recent study of a 420 kV line in Norway is given below:

length of the line, 150 km;

conductor details, three-bundle, single-circuit; and

stretch of line with iceload greater than 10 kg m^{-1}, 47 km.

An uncertainty of ±40% in the design load, resulting from the estimated local variations along the stretch of the line, would mean that savings of a *minimum* of 2 500 000 US$ per year are possible in overhead line investments. On the other hand, insufficient strength in the system may imply enormous extra costs for maintenance and repair. If any field measurement programme could reduce the uncertainty to *ca.* 10–20%, the corresponding uncertainty in the line cost could be reduced to *ca.* 1–1.5 million dollars. A dedicated measurement programme, combined with model calculations, would be justified even if the budget was of the order of 0.5–1 million US$.

However, it is strongly recommended that all such measurement programmes be linked to parallel studies in which collected data are analysed together with relevant meteorological data. The objective for such analyses is to link the relatively short series of load data with meteorological data and construct longer time-series of load 'data' in order to generate general statistical distribution functions of extreme values for design purposes.

Hence, it should be a natural consequence that the power utilities seriously consider investing adequate time and money to reduce uncertainty in the design iceload for a planned new high-voltage transmission line.

In the case of distribution lines, it may not be appropriate or economical for a utility to perform iceload studies only for a new project. However, it should be the responsibility of the utility or a group of utilities in a region to ensure that they have an appropriate programme for improving the design loads. The resources they should put into such programmes must be adjusted according to the expected gains in economic design. This is further illustrated by figures 1 and 2. Applying similar considerations as above, the uncertainty of the iceloads represents potential savings of the order of 12 to 15 million US$ per year for the renewal of wood poles, assuming an average lifetime of 50 years for such poles.

3. Outline of icing processes

A general understanding of different types of icing processes would be very useful in calculating and applying design loads due to icing. The different icing processes are described by the International Electrotechnical Commission as follows.†

Atmospheric icing is a complex phenomenon that can take a number of forms. It is essential that the distinguishing features of these different forms be understood.

Atmospheric icing is a result of two main processes in the atmosphere; they are (i) in-cloud icing; and (ii) precipitation icing.

The precipitation icing occurs in several forms, among which the most important are (i) freezing rain; (ii) wet-snow accretion; and (iii) dry-snow accretion.

In-cloud icing is a process where suspended, supercooled droplets in a cloud (or fog) freeze immediately upon impact on an object exposed to the airflow, for example, a high-level power line above the cloud base.

The ice growth is said to be *dry* when the available heat transfer rate away from the object is greater than the release of the latent heat of fusion. The density of the accretion is a function of the flux of water to the surface and the temperature of the layer. The resulting accreted ice is called *soft* or *hard rime* according to the density. A typical density for soft rime is 300 kg m^{-3} and 700 kg m^{-3} for hard rime.

† Some of the material used in this section is either a direct quote from or a summary of the information in IEC (1997).

The ice growth is said to be *wet* when the heat transfer rate is less than the rate of latent heat release. The growth then takes place at the melting point, resulting in a water film on the surface. The accreted ice is called *glaze*, with a density of 900 kg m^{-3}.

Precipitation icing can occur in several forms, including freezing rain, wet and dry snow. Freezing rain comprises supercooled droplets, which freeze immediately upon impact on objects. The resulting accretion is also *glaze*. The ambient temperature is below freezing point.

When snowflakes fall through a layer of air with temperatures slightly above the freezing point, the flakes may partly melt, become sticky and thus accrete on objects. This is called *wet-snow accretion*. The density and the adhesion may vary widely. If the ambient temperature drops significantly below freezing after a wet layer of snow has accreted, the adhesive and mechanical strength of the layer may become very high. In exceptional cases, wet-snow accretions are known to have occurred with ambient temperatures slightly below freezing.

Dry snowflakes may accrete at temperatures significantly below freezing and can, under conditions of very low wind speed, accumulate on objects to form a *dry-snow accretion*.

It should be noted that the accretion on a conductor might be the result of more than one process occurring during an icing event.

4. Acquisition of iceload data

(*a*) *General*

The most efficient and effective way of collecting data on transmission lines is to monitor selected lines for a sufficient period of time. This method of collecting data may be very challenging and the most expensive, but the usefulness of such data for design and maintenance of overhead lines may have considerably more worth (as outlined in § 3). Field data on ice may come from specially designed measuring racks or test spans. However, the numerous kilometres of transmission lines that pass through areas exposed to icing represent probably the most important source of information. Therefore, these transmission lines represent a major key to improved line design in the future. In particular, such data are the most important source of evaluating the possibilities for upgrading older lines, e.g. by introducing greater conductor diameters, or compact-type conductors, or even increasing the number of sub-conductors (bundles).

Most countries have wind speed maps based on regular meteorological measurements; several of them may have information on the directional distribution of extreme wind speeds. However, the amount of icing data available from meteorological stations is very limited. In many countries, electrical utilities and other institutions maintain sites to measure ice accretion on overhead-line conductors. Utilities should take advantage of this source of information along with that from regular meteorological stations.

In general, iceload measurement on overhead line conductors is complex, time consuming and expensive because special types of measuring techniques are needed to obtain reliable data. It would be ideal if design iceload applied to a certain type of

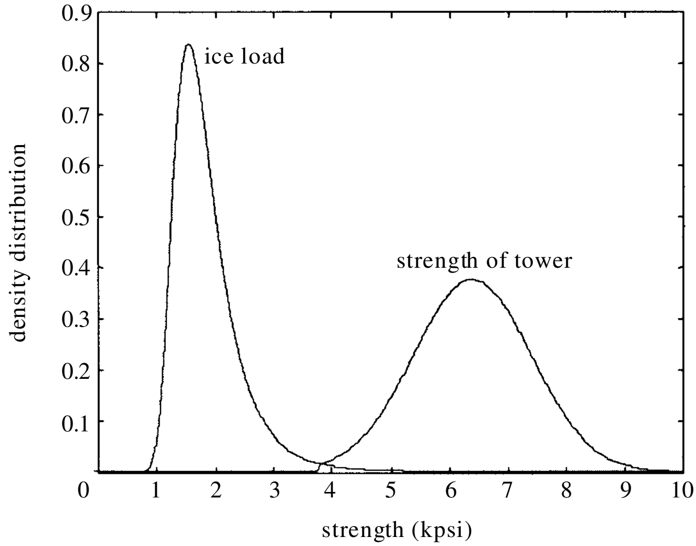

Figure 4. Basis for probabilistic design. Schematic curves for probability distribution of extreme loads, Q, and distribution of strength, h, of towers. It provides a method to calculate an 'acceptable' risk of failure (of the weakest towers) when exposed to loads of a selected return period.

overhead line was based on measurements done on a line with the same mechanical dimensions. However, the costs of obtaining such information could be prohibitive, and therefore simpler and less expensive devices have to be used. The data collected from such devices may have to be transformed to meet the design requirements for the line under consideration.

In this section, some of the data-gathering devices described in IEC (1997) are briefly discussed.

(*b*) *Data for probabilistic design*

IEC (1991) provides the framework for national standards on overhead-line design based on probabilistic methods. A companion report (IEC 1997) provides information on the availability of climatic data, application of simple ice measurement techniques, and icing models for computing iceloads.

Modern transmission-line design is increasingly more often based on probabilistic methods. This means that classical safety factors for loads (load factors) and materials (material factors) are substituted by statistical distributions of extreme loads and material strength. This reflects the fact, for example, that ice loadings occur with a significant magnitude from year to year, and hence that there is no single value which can be defined as a 'maximum iceload' or 'design value' in a rational manner. The design load must reflect the 'risk level', or 'acceptance level' that the owner is willing to pay for. In other words, the design load is selected as a value of low probability, say an event with a calculated recurrence period of 50, 150 or 500 years.

On the other side, the strengths of towers or poles do not have exactly the same specified values. Wood poles especially generally have a great dispersion in strength. The concept of probabilistic design therefore combines the statistical distributions of load and strength in such a way that the owner gets an optimal result regarding the invested cost and target reliability of the line, as illustrated in figure 4.

Upgrading possibilities are already under investigation in many regions where the need for increased transmission capacity cannot be met by building new lines. The economic advantages are very significant if it is possible to utilize existing towers instead of building new structures.

(*c*) *Simple devices to measure iceloads*

The simple devices described in this section are designed to meet the design requirements set in IEC (1991). The IEC recommends annual maximum iceload as the basis for design load calculations, and hence it may be sufficient to measure the mass of ice accretion on a circular rod. The procedure described below will outline the selection of appropriate measurement methods and data deduction. Some of the material used in this section is either a direct quote from or a summary of the information in IEC (1997).

(i) *Dimensions and installation of iceload measurement rods*

A rod 30 mm in diameter and 1 m in length is recommended if the accretion is expected to be less than 15 mm; however, its length should be 2 m if the accretion is expected to exceed 15 cm. It should be noted that a rod longer than 2 m will not significantly improve the accuracy. The rod should be rigid in torsion and bending. When measuring the load caused by glaze, in-cloud icing and dry-snow accretion, the rod may be a smooth cylinder. However, for wet-snow accretions, it is preferable to use a stranded rod, because the growth of a cylindrical snow sleeve can be significantly different for smooth cylinders than for stranded conductors.

A pair of rods should be installed horizontally, one rod normal to and the other parallel to the expected prevailing wind during ice events. The same conditions could also be met by one rod mounted on a rack that is capable of orienting itself to face the wind direction. When icing events are limited to those caused by the dry growth in-cloud icing in which the wind direction is relatively constant, a single rod installed vertically may be sufficient.

In most of the measurements, the rod should be 5 m above the expected highest snow level at the site. However, in some complex terrain, due to the sheltering effect, no ice may accrete on rods installed at a height of 5 m, whereas a large iceload may be observed on rods of at a height of 10 m. For this reason it is useful to consult experts on icing problems when selecting the height of rods. For precipitation icing, the measured values can be used directly. For in-cloud icing, the measured values must be multiplied by a factor to give the basic iceload. If no other information is available, a factor of 1.1 can be used, as defined in IEC (1991).

A simple measurement arrangement consisting of a pair of measurement rods is shown in figure 5. This type of installation is suitable for manual measurement of ice accretion.

(ii) *Procedure for measuring iceloads on simple rods*

Since the main purpose of using simple rods is to obtain only design iceloads, it is sufficient to measure the mass of ice accreted on the rods manually. The mass of the

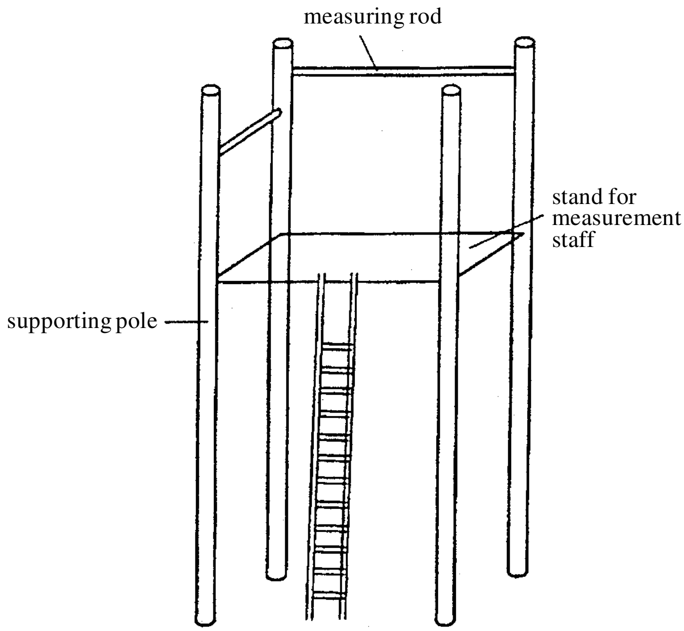

Figure 5. A simple measuring arrangement for manual ice-accretion measurements (after IEC (1997)).

ice rods should be measured immediately at the end of each storm before they are cleaned up and returned to the measurement rack. This is necessary to avoid missing the measurement of the maximum accreted mass, because ice shedding may occur following the storm.

However, it is preferable to have more than one rod in the rack to measure the absolute maximum load to be measured, because more ice may accrete on rods due to new storms even before ice shedding has taken place. Since it is difficult to predict when the ice shedding might take place, it is preferable to have some type of automatic maximum-load indicator. One such indicator for measuring mass due to glaze ice is described below.

(iii) *Automatic load-measuring rod for glaze ice*

The automated iceload-measuring system shown in figure 6 can be used to measure the maximum load due to ice accretion. The automated arrangement essentially consists of a measuring rod, a supporting rod and a load cell to measure the mass of the accreted ice. The arrangement requires power to operate it and could be attached to the tower.

Other types of arrangements are available for measuring load due to in-cloud icing and wet-snow accretion.

(*d*) *Test spans to measure iceloads on transmission-line conductors*

Iceload measurement using test spans is the next best method after making measurements on actual lines.

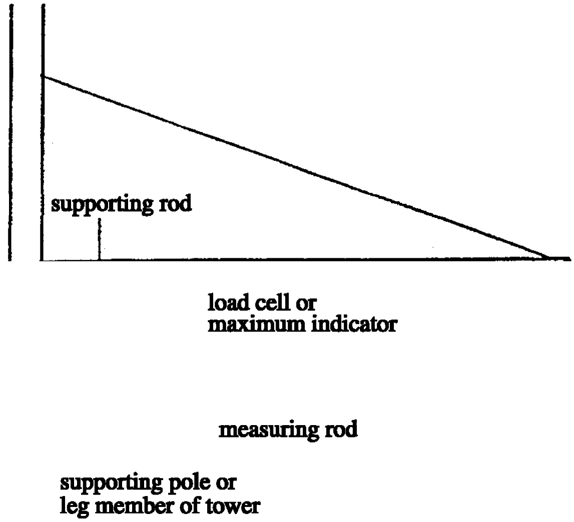

Figure 6. A schematic system for simple automatic iceload measurements (after IEC (1997)).

A test span should be located at a suitable site that generally represents the site for which iceloads are being predicted and can consist of one or more spans. Suitable load cells should be connected at one or both ends of the test span. If there is more than one span, then an intermediate support can be used to measure the vertical iceload. In the case of single-span systems, special measurements are required to distinguish the effects of iceload on conductor tension from load variations due to temperature and wind. Therefore, a one-span set-up is not generally recommended. In the case of a two-span rig, a three-dimensional load cell can be installed in the suspension tower in order to measure the load components in three directions: (i) vertical iceloads; (ii) unbalanced iceloads between adjacent spans; and (iii) wind loads.

Parallel wind measurements are necessary in the last case. However, under icing situations, conventional anemometers will freeze up and may not provide the correct wind speed. If an ice-free anemometer cannot be provided, it is recommended that a relation with wind data from a representative official weather station be established. A correction factor based upon earlier data from similar wind direction and speed range may be applied on the observed wind to give a good estimate of both wind direction and wind speed during the icing event.

All load cells should be specified to operate under the anticipated weather conditions. The length and height of the test line and the number and type of conductors are determined by the objectives of the test site. If necessary, different conductors can be used on the same span for comparative results.

Ideally, the test site should have instrumentation to provide some of the most relevant basic meteorological data required to determine iceloads on conductors. However, some anemometers may freeze up during ice storms and provide no wind speed data. If continuous, accurate wind speed data are required, the use of heated anemometers should be considered. In addition, instrumentation can be installed for special meteorological data such as precipitation and liquid water content.

The test-span site can be monitored manually or automatically; however, automatic operation with periodic site visits to check the instruments is preferable. If automatic operation is used, then a facility such as a telephone should be installed to transfer the data. Video monitoring of the test span could be used and telemetry systems employed to check the site and instrument performance.

More information on measuring rods and test spans can be found in IEC (1991).

(*e*) *Recommendations from the International Organization for Standardization (ISO)*

The ISO (1998) recommends a vertical rotating cylinder of diameter 30 mm as a standard device for ice measurements. The reason for this is that the collected data then have a much more universal value, also for other types of structures. Furthermore, a vertical cylinder reflects icing from all wind directions. In order to detect the direction, a supplementary fixed vertical rod may be included, or the readings should be related to the wind direction.

It is recommended that the ISO standard device is combined with other, structure-specific, installations for iceload measurements.

5. Survey of icing models

An icing model is a tool to predict snow and ice accretion on structures using generally available climatological data. The use of icing models to predict iceload is obviously attractive. Some icing models are relatively simple to use, but are restricted to a particular type of icing. Other models start from more fundamental input data regarding cloud physics and weather parameters and can predict a range of icing types. Some of the icing models will be discussed in this section. Icing models may be employed to estimate iceloads on conductors for certain given conditions and also to generate statistical information on iceloads for determining return periods, etc. Icing models can also be used to enable iceloads to be estimated for lines employing conductors of different diameters, different mechanical characteristics, and at sites with different intensities of icing conditions. Some of the material used in this section is either a direct quote or a summary of the information in IEC (1997).

(*a*) *Types of icing model*

Depending upon the type of data used for their development, icing models may range from empirical to deterministic in their structure.

Empirical models are usually based on climatological databases and measurements of iceload on overhead lines. They often simply represent the relationship between iceloads and climatological data. Hence the empirical models are limited to the range of conditions within which the measurements were made, the specific conductor size upon which iceloads were measured, and the specific locations where the measurements were made. Therefore, extreme care should be exercised in applying empirical models to other situations.

In general, deterministic models describe more completely the physical processes that occur during icing. They are mostly time dependent, and more detailed climatological data are required; in particular, information on liquid water content and droplet sizes. As such data are not generally available, they have to be deducted from ordinary climatological data. This means that these models require data such as wind

Table 2. *Climatological data required for applying icing models*

model	input data	output data
glaze ice	wind speed wind direction temperature and precipitation rate	mass of ice and radial thickness of ice deposit
rime ice	wind speed normal to object temperature cloud base cloud cover and type liquid water content droplet size and relative humidity	mass of accreted ice and density of accreted ice
wet snow	temperature water fraction of snow precipitation rate and snowflake size	mass of accreted snow
rime ice and wet snow	perpendicular wind speed temperature liquid water content droplet size precipitation rate relative humidity torsional stiffness of conductor span length	iceload across the span, rotational state of the conductor and shape of the accreted surface

speed, wind direction, air temperature, precipitation rate, relative air humidity, air pressure, visibility, cloud cover, cloud type, and vertical stability.

However, in reality, some essential input data, such as liquid water content and droplet size, are generally not available from databases and have to be determined empirically.

It is important to note that the accuracy of the iceload predictions depends upon the quality of input climatological data. In addition, the climatological data should represent the site for which iceloads are being predicted. It is advisable to calibrate icing models for the specific structures, climatological conditions and topographical locations of their intended use.

(*b*) *Application of icing models*

Several models are available to predict the three main types of icing: glaze, rime and wet snow. Some models can simulate all three types of icing, while others apply to only one of the processes.

Some icing models described below provide an illustration of the type of climatological data required for using icing models and the form of estimated ice-accretion values. The climatological data required to apply these models and the type of output data are listed in table 2.

A simple model to simulate glaze ice (Chaine & Skeates 1974). In this model the equivalent radial ice thickness is calculated from ice thickness accreted on vertical and horizontal surfaces. These thicknesses are essentially functions of wind speed and direction, temperature and precipitation rate. The calculated radial ice thickness

Table 3. *Local exposure factors (LEFs) for predicting iceloads (for terrain types (TTs) see figure 8)*

TT: steep slope	LEF	TT: steeper slope	LEF	general description	general comments
A1	0.8	A2	0.8	valley bottom	if a terrain at a location falls between two types shown in the table, use the average LEF values
B1	1.0	B2	1.0	rolling	in deciding the LEF for a location, the nature of the terrain up to 3 km around the location is considered
C1	1.1	C2	1.1	flat	'steep slope' is up to 300 m km^{-1}
D1	1.2	D2	1.4	$\frac{1}{3}$ point of slope	'steeper slope' is 400–500 m km^{-1}
E1	1.6	E2	2.0	mid-point of slope	
F1	2.0	F2	2.5	$\frac{2}{3}$ point of slope	
G1	2.4	G2	3.0	top edge of valley	
H1	2.8	H2	3.5	hill top	
misc.	1.2	—	—	fjord/valley crossing	

is corrected by a factor that depends on air temperature and the iced conductor diameter. The data required for applying the model and the output values are shown in table 2.

A model to simulate rime ice (Makkonen 1984). This model simulates only rime icing, which is assumed to maintain a circular shape on overhead line conductors. A collection efficiency calculation of the conductor shape is performed using well-established parametric equations. The portion of intercepted water that actually freezes (freezing fraction) is calculated, based on the heat-balance equations of the icing surface. Depending on the freezing fraction, the ice growth can either be dry or wet. In wet growth, ice accretion is determined by the heat-balance equation of the surface; however, in dry growth, ice accretion is only a function of collection efficiency. This model considers explicitly the effect of changing ice-accretion diameter.

The data required for applying the model and the output values are shown in table 2.

A model to simulate wet snow (Sakamoto & Ishihara 1984). This is a semi-empirical model for wet-snow accretion only. The version of the model assumes that snow accretion depends on the precipitation rate, the fall speed of snow, the wind speed, the air temperature, the snow accretion rate, and the mean snow density. The mean snow accretion rate and the mean snow density are determined from limited observed data for different seasons and meteorological situations. The model considers snow melting as well as snow shedding and deflection of snow particles from overhead lines.

The data required for applying the model and the output values are shown in table 2.

Model to simulate rime ice and wet snow (Poots & Skelton 1990, 1991). These three-dimensional, time-dependent, mathematical models predict ice growth on a conductor of finite span and finite torsional stiffness. The ice-accretion kinetics is formulated by using a simulated airflow approximated by either attached potential flow or a computer fluid dynamics (CFD) code. These models include thermodynamic aspects of the transition from rime to glaze and the determination of the liquid water content of a wet-snow deposit, together with the reconstitution of wet-snow loads from historical weather data.

The data required for applying the model and the output values are shown in table 2.

(*c*) *Potentials for the use of meteorological boundary-layer models*

Any model for iceload prediction must be based on available meteorological data for the area in question. In particular, for in-cloud icing, general meteorological data are not fully adequate for use in models, since they do not include parameters on cloud physics, like liquid water content and droplet sizes. As the models are very sensitive to these parameters, they have to be evaluated indirectly, based on interpretations of cloud type and cover, temperature, vertical stability, wind speed, up-wind conditions of sea, land and topography, precipitation rates, etc. Such indirect methods are usually unreliable and can only give indications of the icing conditions (Ervik & Fikke 1984).

However, the development of atmospheric boundary models has provided tremendous steps forward, during the last decade, in the description of the water cycle in the lower atmosphere (troposphere). The so-called 'limited area models' (LAMs) now in general use for daily weather forecasts often have a grid distance of 50 km or less. Models with a 1 km grid will probably be introduced in many countries in the near future. This means that the topography, as well as the meteorological parameters, are represented as 'averages' of 1 km, with a corresponding resolution in topology.

One obvious consequence of this development is that quantitative forecasts of clouds and precipitation are significantly improved. These models will accordingly be better in describing phase transitions of water between vapour, liquid and frozen aggregates. In Vassbø (1998) an attempt was made to calculate the water content of clouds from such models. The results, as shown in figure 7, were promising; however, further model developments and more detailed topography descriptions are needed for practical application of this approach.

Figure 7 shows an example of calculations from this study.

6. Effects of terrain on ice loading

The basic icing models generally predict loads that are essentially applicable to overhead power lines in an open terrain that is free of any major obstructions such as valleys, mountains or forests. However, in reality, a power line will very rarely run only through open terrain. A line running along a valley could be sheltered from the effects of high wind. On the other hand, a line located along a mountain peak may be subjected to higher loads than one in open terrain. Hence, it is important that predicted iceloads are corrected appropriately to account for the various terrain conditions through which a power line is expected to run.

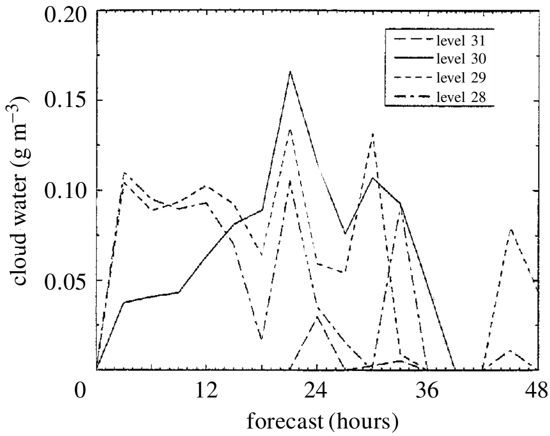

Figure 7. Model calculations of water content at different levels over a hill in Finland (after Vassbø 1998). (Prognostic calculations up to 48 h.)

The correction factors could either be incorporated into the method for calculating iceload or applied to the load after it is calculated. In this paper, the terrain factors, also called the local exposure factors (LEFs), are estimated for assessing iceloads for a transmission-line route in southern Norway by Krishnasamy & Fikke (1996, 1998).

In choosing the terrain factor, the nature of the terrain and its immediate surroundings should be carefully considered. The terrain factor for each location is chosen by carefully evaluating its characteristics and comparing them with those of a reference location.

To make the selection of LEF values easier, the terrain types are divided into several basic categories, and for each category a different LEF value is assigned. The description of the various terrain types and the corresponding LEF values are given in table 3 and figure 8. Each terrain is divided into two sub-terrains depending upon its average slope with respect to a reference flat terrain. The LEF values for any terrain that does not match the standard terrain types are determined from the LEF values given in table 3.

Higher LEF values are assigned for terrain with steep slopes, or for fjord and valley crossings, compared with flatter terrains.

7. Case study 1: loads due to glaze ice in Ontario, Canada

A method is described to calculate vertical iceload and wind-on-iceload on ice-covered conductors in Ontario. The calculation of wind-on-iceload is complex because there are almost no measured data available on combined wind and ice. The method chosen for the study uses historical weather data such as wind, temperature and precipitation and an icing model for glaze ice.

(a) *Ice and wind-on-ice*

The information on annual extreme ice and wind-on-ice is derived from the Chaine & Skeates (1974) icing model. As described earlier, the ice accretion from this model is defined in two parts, ice accretion on the horizontal surface (A_h) and ice accretion

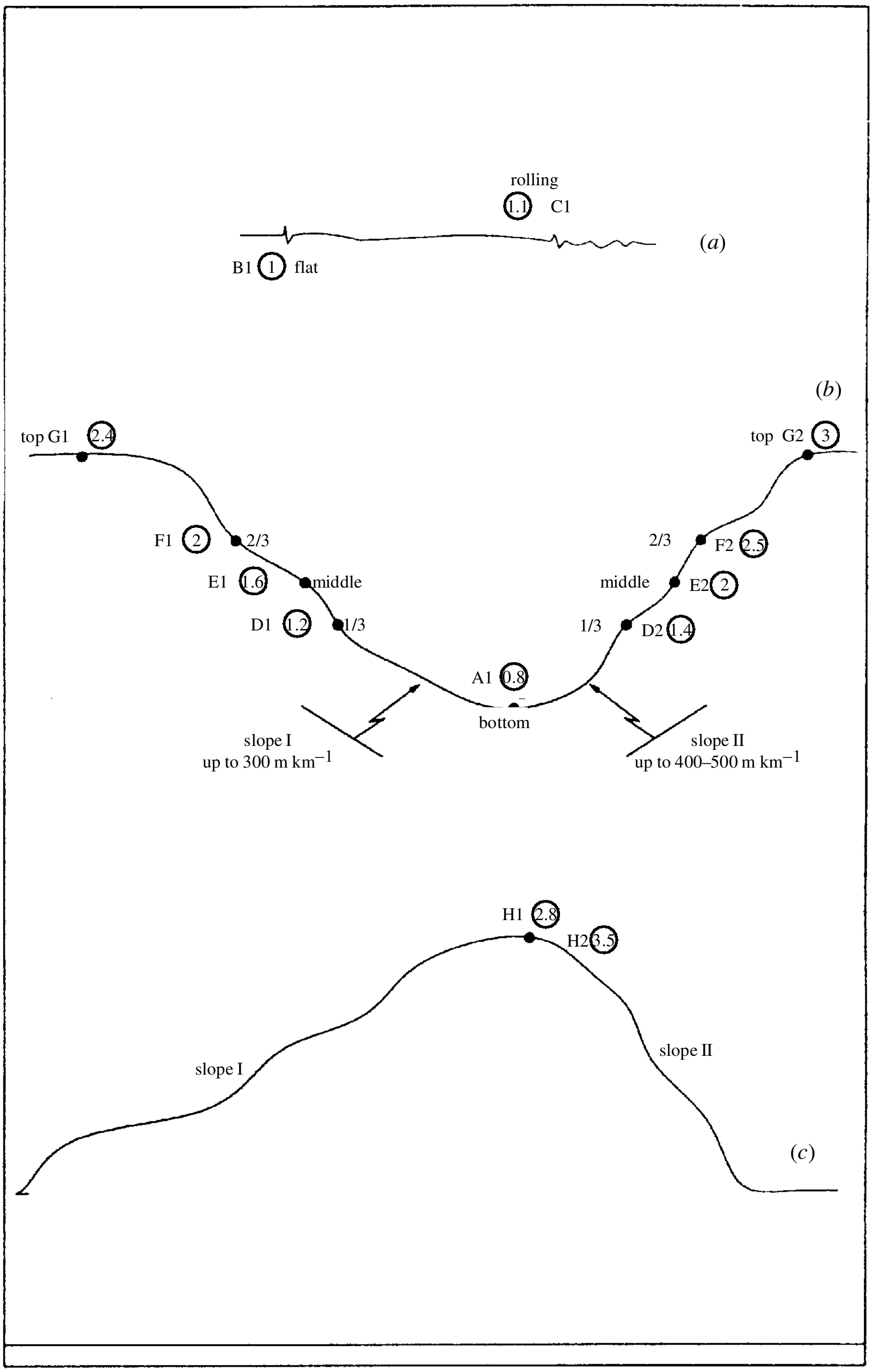

Figure 8. Description of various terrain types (see text): (*a*) flat and rolling terrain; (*b*) valley; and (*c*) hill top.

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on the vertical surface ($A_{\rm v}$). From the $A_{\rm h}$ and $A_{\rm v}$ values, the equivalent radial ice thickness on a conductor, t, is calculated using

$$t = [\tfrac{1}{2}kr(A_{\rm h}^2 + A_{\rm v}^2)^{1/2} + r^2]^{1/2} - r, \tag{7.1}$$

where k is a correction factor depending on the conductor size and temperature, $A_{\rm h}$ is the ice accumulation on the horizontal surface, $A_{\rm v}$ is the ice accumulation on the vertical surface and r is the conductor radius.

In choosing the annual extreme ice and the annual extreme wind-on-ice data, the following steps are used.

Assume that there are n ice storms *during a given year.*

(1) For each of the n ice storms calculate

  (a) the maximum equivalent radial ice accretion, and
  (b) the maximum wind-on-iceload (m for a 25 mm reference conductor).

(2) From the calculated values of ice accretion (step 1(a)) and wind-on-iceload (step 1(b)), *two ice storms* are selected:

  (a) one providing the maximum ice accretion, and
  (b) the other yielding the maximum wind-on-iceload

(3) The ice storm providing the maximum equivalent radial ice represents the annual extreme ice data, from which the annual extreme load due solely to ice is calculated. The ice storm yielding the maximum wind-on-iceload provides the annual extreme wind-on-ice data.

(*b*) *Prediction of iceload*

The vertical load on an overhead conductor due to ice is calculated from the following relationship:

$$P_{\rm I} = \pi\rho[(D + 2t)^2 - D^2]L, \tag{7.2}$$

where ρ is the density of ice, D is the conductor diameter, t is the equivalent radial ice thickness, L is the span length for which the load is calculated, and $P_{\rm I}$ is the iceload.

Using the procedure described in § 8 *a* and the above equation, the annual extreme radial ice and the corresponding iceloads are calculated.

(*c*) *Prediction of wind-on-iceload*

The wind-on-iceload is calculated by using the following relationship and the procedure that is outlined in § 7 *a*:

$$P_{\rm WI} = SV^2(D + 2t)L, \tag{7.3}$$

where S is the shape or span factor obtained from field or laboratory studies, D is the conductor diameter, L is the span length for which the load is calculated, V is the maximum mean wind speed during an ice storm, t is the equivalent radial ice thickness, and $P_{\rm WI}$ is the wind-on-iceload on the conductor.

By applying the procedures described above, the annual extreme iceload and the annual extreme wind-on-iceload are calculated for about 30 weather stations in Ontario (Krishnasamy & Tabatabai 1988). The annual extreme load values for 19 years from one of the stations are given in table 4.

Table 4. *Iceload and wind-on-iceload for Toronto International Airport*

	extreme iceload		extreme wind-on-iceload		
year	radial ice (mm)	load (N)	radial ice (mm)	wind speed (km h^{-1})	load (N)
1953	7.9	2.2	7.9	41.0	1.6
1954	4.1	1.0	0.0	70.3	2.4
1955	4.1	1.0	0.0	51.3	1.4
1956	6.6	1.8	1.3	82.0	3.4
1957	2.0	0.4	1.0	50.0	1.4
1958	1.8	0.4	1.0	39.6	1.0
1959	10.7	3.2	6.4	50.0	2.0
1960	20.6	8.1	3.0	60.3	2.3
1961	15.7	5.5	15.7	82.0	7.0
1962	7.9	2.3	0.3	61.4	1.9
1963	3.8	0.9	2.3	82.0	3.6
1964	5.3	1.4	5.3	58.5	2.5
1965	14.0	4.7	14.0	60.0	3.8
1966	6.6	1.8	1.5	55.8	1.8
1967	7.6	2.2	6.6	55.8	2.4
1968	23.1	9.7	23.1	62.7	5.5
1969	5.1	1.3	5.1	54.0	2.1
1970	3.3	0.8	2.8	71.0	3.0
1971	12.2	3.9	12.2	58.5	3.4

Table 5. *Iceload and wind-on-iceload for various return periods for Toronto International Airport (Krishnasamy & Tabatabai 1988)*

return period (yr)	radial ice (mm)	ice load (N)	wind-on-ice load (N)
10	12.7	4.2	2.0
20	15.2	5.3	2.3
40	17.8	6.6	2.6
50	18.5	7.0	2.7
60	19.3	7.3	2.8
80	20.3	7.9	2.9
100	21.1	8.4	3.0

(*d*) *Return period values for radial ice, iceload and wind-on-iceload*

The database developed above is used to predict radial ice, iceload and wind-on-iceload for various return periods. This is achieved by performing Gumbel type I extreme-value analyses on radial ice, iceload and wind-on-iceload data.

The extreme-value analyses done on radial ice, iceload and wind-on-iceload are used for estimating the amount of radial ice, iceload and wind-on-iceload for any return period. The values of ice, iceload and wind-on-iceload for a given return period can be estimated from

$$\text{return period} = \frac{1}{1 - \exp[-\exp(\text{RV})]}, \tag{7.4}$$

where RV (reduced return variate) equals $(X - B)/C$, and X is the value of ice, iceload or wind-on-iceload.

In the above equation, B and C are the location and space parameters of the Gumbel type I distribution based on the observed data. The values of the constants B and C are calculated for all 30 weather stations in the database. Using these parameters and the procedure discussed above, the values of radial ice, iceload and wind-on-iceload are estimated for various return periods. A set of such values for Toronto International Airport is given in table 5.

It should be noted that in climatology it is often assumed that extreme analyses should not be made for more than twice the length of the time-series. This means that 20–25 years of data are necessary for calculating a climatological parameter with a return period of 50 years. When values for longer return periods are calculated, it should be remembered that this is more a consequence of the need for an objective method, rather than an expression of the real expectation of the weather event in question.

8. Case study 2: wet-snow loads in southern Norway

A procedure is described to predict wet-snow loads for a new 420 kV transmission line in southern Norway. This procedure utilizes available information such as historical precipitation data and known or established wet-snow loads at certain stations along the general vicinity of the line route. The procedure takes into consideration the effects of climate, elevation, terrain and historical experience.

(a) *Predicting wet-snow loads at weather stations*

Before describing the procedure to predict wet-snow loads along a transmission-line route, it will be useful to discuss the procedures for predicting the loads at individual weather stations. A related study by the Norwegian meteorological institute (DNMI 1996) was based on the assumption that the distribution of wet-snow loadings is correlated with the expected extremes of precipitation during the winter months. It was further assumed that the one that uses the average of the first five precipitation values provides the best estimate for predicting wet-snow loads. The steps in choosing the reference precipitation values are described below.

(a) From historical data for each station, calculate the average of the first five values for each month of the winter season (October–April).

(b) From the precipitation values for these seven months select the maximum value for each station during the same period of years (at least 20–30 years).

(c) Affix the precipitation value found in (b) from one station where the iceload is known (or otherwise established), and use this as a reference iceload.

(d) Establish wet-snow loadings on each of the other stations according to the ratios of the precipitation values.

Table 6. Average of the five highest daily extreme precipitation values for the meteorological stations along the route for the 420 kV transmission line Kristiansand–Holen; the highest of these (shown in bold) are used for wet-snow evaluations

station number	station name	years of data	height above sea level (m)	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
3904	Kjevik	37	12	**71.5**	69.0	53.0	54.6	53.2	55.9	40.4	44.34	37.92	65.64	66.06	76.0
3910	Oksoy fyr	37	9	**57.5**	57.2	47.9	51.8	43.9	45.3	32.9	35.18	32.8	56.44	61.1	67.7
3969	Byglandfjord–Solbakken	23	212	**62.3**	54.2	43.7	39.4	37.9	33.9	39.0	34.82	35.78	48.5	47.3	49.9
4088 (4086)	Hovden–Lundane (A)	12	765	11.2	21.8	16.5	**23.7**	6.3	9.0	9.6	16.44	8.48	11.54	4.28	21.4
3838	Dovland	35	259	**68.3**	66.7	48.1	44.4	36.9	45.7	40.4	42.16	32.32	55.48	62.02	63.3
3922	Mestad i Oddernes	93	151	**87.5**	86.1	83.1	79.6	82.4	82.6	56.6	67.38	59.64	76.46	81.94	106.9
3955	Hannasmyran	22	190	**63.4**	46.4	47.9	44.3	39.3	43.6	28.4	46.62	35.54	47.12	55.02	60.1
3984	Austad–Ekron	21	207	**44.9**	39.6	35.6	34.2	34.3	23.9	22.0	33.22	34.1	42.3	49.8	47.7
4020	Brokke kraftstsajon	7	270	**37.2**	29.6	29.7	37.0	27.4	25.8	19.2	10.74	16.14	37.08	28.26	23.3
4027	Homme	28	364	**56.4**	39.9	36.8	31.8	25.8	24.6	27.3	37.46	46.92	45.96	40.64	51.0
4042	Bykle–Kultran	27	599	36.7	33.5	34.8	**45.2**	37.3	30.8	18.2	28	44.78	39.66	31.7	41.0
4090	Bjaen	37	920	34.0	33.7	**44.4**	41.0	39.0	40.6	24.0	23.76	31.92	35.36	32.16	35.7

Table 7. *Reference weather stations and precipitation values for predicting iceloads*

sector	reference station	precipitation value (mm)
Kristiansand–Evje/Vegusdal	Mestad i Oddernes	87.5
Evje/Vegusdal–Brokke	Byglandsfjord	62.3
Brokke–Holen	Homme	56.4

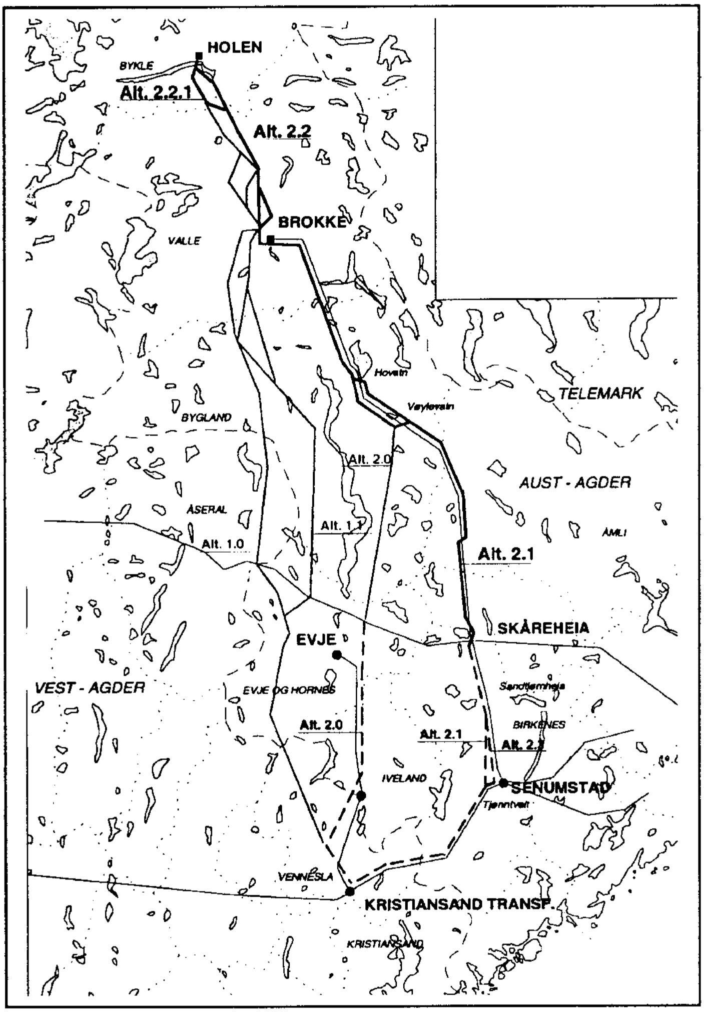

Figure 9. The 420 kV transmission line from Kristiansand to Holen. The final route follows the alternatives 2.1 and 2.2 on the map.

For the corresponding precipitation data from the selected stations, see table 6.

The independently estimated precipitation values (given in table 7) for stations 3922 Mestad i Oddernes, 4027 Homme and 3969 Byglandfjord are used in further calculations to predict wet-snow loads along the proposed line route.

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(*b*) *Predicting wet-snow loads along a line route*

The procedure to predict wet-snow loads along a proposed line route utilizes some of the recommendations made in a report on weather statistics for transmission-line rights-of-way (DNMI 1996). Based on this report, the line between Kristiansand and Holen (see figure 9) is divided into three main sectors for prediction of iceloads. For each of these sectors a reference weather station is chosen, the data from which are used in part for predicting wet-snow loads on transmission lines in these sectors.

Once the reference weather stations are chosen for the three sectors, the procedure described below is used to predict wet-snow loads at various locations along the proposed line.

Step (1). The first step in predicting the iceload is to choose from table 7 the precipitation amount for each of the three reference stations along the Kristiansand–Holen corridor.

Step (2). The next step is to evaluate the precipitation amount for each individual location as shown below.

The following relationship (taken from DNMI (1996)) is used for predicting the precipitation amount at each location:

$$p = p_0\{1 + 0.0005(h - h_0)\}, \tag{8.1}$$

where p is the precipitation at the location (mm), p_0 is the precipitation at the reference station (mm), h_0 is the height of the reference station above sea level (m), and h is the height of the location above sea level (m).

Since each sector has a unique reference station, care should be exercised in choosing the correct reference precipitation values.

Step (3). The next step is to predict the wet-snow loads for each location as shown below.

It is assumed that the iceload at a certain location, L, is proportional to the precipitation amount p, and can therefore be predicted from the following simple relationship:

$$L = \left\{\frac{\text{iceload at Kjevik}}{\text{precipitation at Kjevik}}\right\} \times \{\text{precipitation at location } p\}, \tag{8.2}$$

where Kjevik is the selected station for which the iceload is fairly well established (see the example in table 9, where location p is the meteorological station Mestad i Oddernes)

The above predicted iceload includes the effects of elevation above sea level and distance from the coast, but no other effects. The factors described in the following include the effects of terrain and possible historical information about the location.

Terrain factor or LEF: the LEF for predicting iceloads is chosen as described in § 6.

Historical experience factor (HEF): the HEF is introduced to account for the effect of unusual and unique historical ice storms. The factors are estimated from the available information on unique storms in the area under consideration. It is very important to include the effects of unique storms to avoid under-design and consequent potential for premature line failure.

Table 8. *LEF values for the* 420 kV *line Kristiansand–Holen*

((1) If a terrain at a location falls between two types shown in the table use the average LEF values. (2) In deciding the LEF for a location, the nature of the terrain up to 3 km around the location is considered. (3) Moderate slope is up to 300 m km^{-1}. (4) Steeper slope is 400–500 m km^{-1}.)

TT: moderate slope	LEF	TT: steeper slope	LEF	general description
A1	0.8			valley bottom
B1	1			rolling
C1	1.1			flat
D1	1.2	D2	1.4	one-third point of slope
E1	1.6	E2	2	mid-point of slope
F1	2	F2	2.5	two-third point of slope
G1	2.4	G2	3	top edge of valley
H1	2.8	H2	3.5	hill top
	1.2	—	—	fjord/valley crossing

Table 9. *Summary of procedure to establish iceloads at location number 4 (see table 8)*
(Reference station: Mestad i Oddernes.)

precipitation amount for reference station	87.5 mm
height above sea level	151 m
location number for which iceload is predicted	4 (table 8)
height above sea level	280 m
estimated precipitation (using (8.1))	$87.5\{1 + 0.0005(280 - 151)\} = 93$ mm
predicted iceload (using (8.2))	$(7/71.5)(93) = 9.1$ kg m^{-1}
LEF (table 8)	1.1
HEF	1.0
predicted iceload (modified)	$(9.1)(1.1) = 10$ kg m^{-1}

Step (4). The next is step is to calculate the modified iceload by multiplying the previously determined iceload, p, by the two factors:

$$p_{\mathrm{m}} = p(\mathrm{HEF})(\mathrm{LEF}),$$

where p_{m} is the modified iceload. Some typical LEF values for selected terrain slopes for the Kristiansand–Holen corridor are given in table 8.

(*c*) *An example to predict iceloads at various locations*

There are a total of 88 locations along the corridor for which the iceloads are predicted. As stated earlier, the corridor is divided into three sectors. The load prediction for one location along the Kristiansand–Evje/Vegusdal sector is shown in table 9.

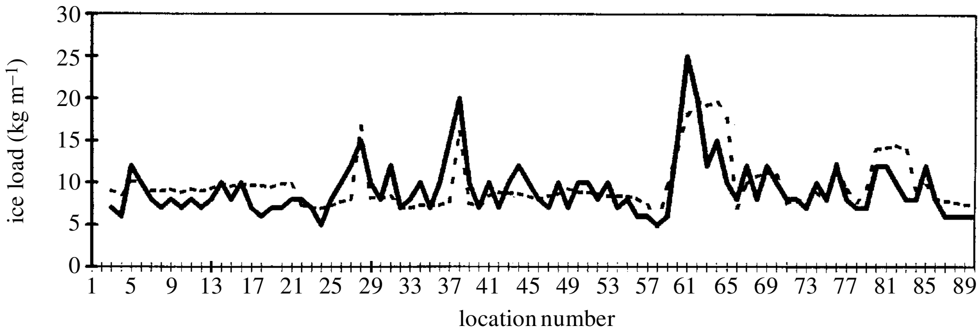

Figure 10. Wet-snow loads predicted by the described procedure (dashed line) and estimated by subjective methods (solid line).

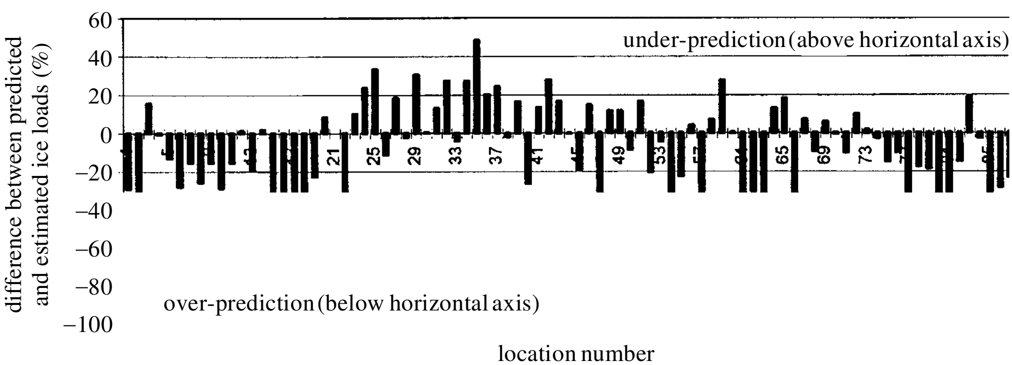

Figure 11. Relative differences between estimated and predicted wet-snow loads as shown in figure 10.

(*d*) *Comparison of predicted and estimated iceloads*

By applying the above procedure, wet-snow loads are predicted for a total of 88 locations along the corridor and some typical values are listed in table 8 along with all the other relevant information, including the estimated design loads. The predicted values for the 88 locations are plotted with the estimated design loads in figure 10. The differences between the predicted and estimated iceloads are compared in figure 11, in which the values above the horizontal axis are over-predicted and the values under the axis are under-predicted.

Analysis shows (see figure 11) that the procedure over-predicted the iceload 49 times (55%), under-predicted it 33 times (38%) and correctly predicted it six times (7%). When comparing the two sets of values, the nature of data available, the type of terrain to deal with and also the methods employed in deciding the estimated loads should be considered. Each of these parameters are very difficult to quantify. They will, however, influence the end results significantly.

Therefore, in general, the predicted loads are correlated reasonably well with the estimated values, except at a few locations such as fjord and valley crossings. The procedure is intentionally set to predict high loads at valleys and mountain crossings to allow for the potential extreme exposure conditions.

9. Summary and conclusions

The objective of this paper is to study the various aspects of assessing climatological loads on overhead power lines. In order to achieve this objective, the paper discusses in detail each of the following important topics.

(i) Icing types to consider.

(ii) Available icing models.

(iii) Influence of topography on iceload.

(iv) Sources of information and availability of icing data.

(v) Economical consequences of ice loading on power lines.

(vi) Uncertainties of ice loading and its effect on return periods.

(vii) Recommendations for data gathering.

It has been shown that if the various parameters that affect ice loading are not seriously considered, the resulting design might not be economical; in some situations it may even lead to under-design. In order to explain the influence of some of these parameters, typical case studies are included wherever possible.

It is highly recommended that, whenever possible, field studies should be part of any important project. The field studies must include measurements of relatively short series of iceload that could be linked with meteorological data for further analysis to generate statistical extreme-value functions for design purposes.

Hence, it is recommended that the power utilities, either individually or as a group, seriously consider investing an adequate amount of time and money in reducing uncertainty in the design iceload for new or to-be-upgraded high-voltage transmission lines.

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