Collecting and using weather data for the design of overhead lines according to IEC 60826

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Abstract—**IEC TR 60826 introduced the probability concept in the design of overhead electric power lines. While statistical distributions of wind speeds are available at national meteorological services, similar information on ice loadings can only be provided by utilities themselves. This paper describes the consequences for investment costs in power lines due to uncertainties in ice load assessments, as well as the importance of long time series of both wind and ice data.**

I. INTRODUCTION

The International Electrotechnical Commission (IEC) has published Technical Report 60826 which was the first international recommendation on design of overhead lines based on reliability concepts [1]. This report deals with methods to calculate wind and ice load on overhead lines starting with measurements and field observations of wind speed and ice accretion.

Ice- and wind loads on conductors and earth wires are the most important environmental factors for the mechanical design of overhead lines. Wind has by itself a universal meteorological interest and wind loads have a wide common interest for the design of all types of structures as well as for transportation on roads, at sea and in the air.

Ice loads on structures and overhead power lines are, on the other hand, mainly of interest for the electric power utilities and telecommunication companies in areas exposed to ice and snow accretions. This fact reflects the large differences in quality of the statistical databases for wind and ice loads. Wind data are generally available with sufficient quality from most meteorological offices, while acquisitions of ice data are quite rare.

This paper addresses the importance of long-term recording/measurements of weather data and describes how these may be utilized according the 60826 report for the design of overhead lines.

II. DESIGN METHODOLOGY IN IEC 60826

It is demonstrated in IEC 60826 that if a load Q_T (load having a return period T) is associated with a strength of components corresponding to the 10% exclusion limit, the resulting reliability is almost constant and equal to 1/(2T) in the normal range of variation of Q and R. Thus, the accuracy of the estimates of Q_T becomes quite important if one aims to design lines according to a target reliability level.

In the following examples, the importance of increasing the number of years of wind and ice data is demonstrated and the economical benefits of such programs of recording ice and wind data are demonstrated.

III. EXAMPLES OF WEATHER DATA FOR ICE AND WIND

For the purpose of comparisons, the same set of observations on ice and wind loads are used in this paper as those presented in CIGRÉ Technical Brochure 109: Review of IEC 826 "Loading and Strength of Overhead Lines" [2]. The ice and wind load data are described in the following paragraphs.

A. Ice

Time series of ice loadings are according the following recorded annual maxima of ice loadings[1]:

Year	Ice load (N/m)	Year	Ice load (N/m)
1980	10	1986	8
1981	9	1987	6
1982	8	1988	7
1983	11	1989	34
1984	32	1990	4
1985	3	1991	23

From the observations above the average ice load value is calculated to 12,9 N/m and the standard deviation to 10,7 N/m, i.e. a coefficient of variation equal to 0,82.

The number of years with observations, the average value and the standard deviation are the necessary parameters for making the statistical analyses of design wind and ice loads for an overhead line.

B. Wind

The time series of the maximum annual 10 min. wind speeds (perpendicular to the line) is measured 13 m above ground in terrain with ground roughness B for 29 years:

Year	Wind speed (m/s)	Year	Wind speed (m/s)
1956	16,5	1971	15,4
1957	15,4	1972	15,4
1958	17,0	1973	20,6
1959	15,9	1974	15,4
1960	25,7	1975	13,4

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[1] In this example, ice data is assumed to be measured as a unit weight per conductor length. alternatively, ice data can also be expressed in radial ice thickness

1961	13,4	1976	18,5
1962	15,4	1977	12,9
1963	14,4	1978	13,4
1964	16,5	1979	14,4
1965	15,4	1980	14,9
1966	22,6	1981	14,4
1967	17,5	1982	13,9
1968	15,4	1983	17,0
1969	13,4	1984	14,9
1970	17,5		

From the observations the average wind load value is calculated to 16,1 m/s and the standard deviation to 2,8 m/s, i.e. a coefficient of variation equal to 0,18.

IV. Calculation of climatic design loads for overhead lines according IEC 60826

A. Reliability levels

The design loads are calculated according to the chosen reliability level given by the return period of the climatic load. In IEC 60826 the reliability levels are defined in Table 1 below.

Table 1. Reliability levels for overhead lines

Reliability levels	**1**	**2**	**3**
Return period, T, of climatic design loads, in years	50	150	500

B. The Gumbel distribution function

The climatic design loads according to these reliability levels may be calculated using the Gumbel cumulative distribution function. Equation (1) below gives the probability $F_{(x)}$ of not exceeding the value *x*.

$$F_{(x)} = e^{-e^{-\frac{x-p_1}{p_2}}} \qquad (1)$$

Where

$$p_1 = \bar{x} - \frac{C_2}{C_1}\sigma \qquad (2)$$

$$p_2 = \frac{\sigma}{C_1} \qquad (3)$$

where

$\bar{x}$ = average value
σ= standard deviation

The factors C_1 and C_2 depend on the number of observations in a measurement series. For a measurement period of n years, the value z_i is calculated as follows:

$$z_i = -\ln(-\ln\frac{i}{n+1}) \quad where\; 1 \le i \le n \qquad (4)$$

$$C_1 = \sigma_z = \sqrt{\frac{1}{n}\sum_{i=1}^{n} z_i^2 - z_m^2} \qquad (5)$$

i.e. C_1 is the standard deviation of the z_i values

$$C_2 = \bar{z} = \frac{1}{n}\sum_{i=1}^{n} z_i \qquad (6)$$

i.e. C_2 is the average of the z_i values.

It is noted that the above form of the Gumbel distribution incorporates a bias for the number of years of data. This form is the one preferred in IEC 60826. In some other cases, the general form (C1=0.57722, C2= 1.28225) have also been used.

C. Design load with return period T

Equation (1) gives the probability F(x) of not exceeding the value *x*. The probability of not exceeding the value *x*(T) i.e. the value with a return period equal to T is:

$$F(x(\mathrm{T})) = 1 - 1/\mathrm{T} \qquad (7)$$

If the natural logarithm is taken twice on both sides of the equal sign of equation (1) the result is:

$$\ln(-\ln F(x(\mathrm{T}))= \frac{x(\mathrm{T}) - p_1}{p_2} \qquad (8)$$

Inserting the expressions for p_1 (equation 2), p_2 (equation 3) and F(*x*(T)) (equation 7), we get the following relation for the design value and return period T:

$$x(\mathrm{T}) = \bar{x} - \frac{C_2}{C_1}\sigma - \frac{\sigma}{C_2}\ln\left[-\ln(1-\frac{1}{\mathrm{T}})\right] \qquad (9)$$

Equation (9) shows that the climatic design value calculated by the Gumbel distribution function, only depends on the chosen return period, T, average value, $\bar{x}$, standard deviation, σ, and number of observations (i.e. the constants C_1 and C_2).

V. Numerical example of Design loads for ice and wind observations in CIGRÉ brochure 109

A. Ice loads

The average value for the 12 annual maximum ice load values is 12,9 N/m, and the standard deviation is calculated to 10,7 N/m that means a variation coefficient of 0,8 (80%). This is somewhat higher than the indicated variation of 0,7 in IEC

60826. If a return period of 50 years is chosen (often used for electric distribution systems) the design value according to equation (9) is calculated to be approximately 50 N/m. If now the design load is calculated for different number of years of observations based on *the same fixed average value of 12,9 N/m and standard deviation of 10,7 N/m,* the resulting design loads for a return period of 50, 150 and 500 years are calculated in table 2 below.

TABLE 2. DESIGN ICE LOADS AS FUNCTION OF NUMBER OF OBSERVATION YEARS

Number of years	**C - coefficients**		**Design ice loads** (N/m)		
			Return time T years		
n	**C_1**	**C_2**	**50**	**150**	**500**
5	0,458794	0,792778	59,2	74,0	90,2
10	0,495207	0,949625	51,1	63,5	77,0
20	0,523552	1,062822	46,8	57,8	69,9
30	0,536221	1,112374	45,1	55,7	67,3
40	0,54362	1,141315	44,2	54,6	65,8
50	0,548542	1,160661	43,7	53,8	64,9
60	0,552084	1,174665	43,3	53,3	64,2
100	0,560023	1,206489	42,4	52,2	62,8
200	0,567153	1,235977	41,6	51,2	61,6
300	0,569926	1,247866	41,3	50,8	61,1
400	0,571437	1,254501	41,2	50,6	60,8
500	0,572398	1,2588	41,1	50,4	60,6
∞	0,57722	1,28255	40,5	49,7	59,7

The ratio of the design ice load values based on only 5 observations to the design ice load values based on an infinite number of observations is about 1,5. This means that if you have a statistical basis of only 5 years with observations, the design value in this case is 50% higher than a design value based on infinite number of years with observations. The main reason for the large uncertainty for a low number of years with observations for ice loads is the high value of the standard deviation of the observations. Even if you have observations for more than 30 years, a couple of years with unusual or low high ice loads may influence the design load.

If 10 years of observations is chosen as reference, Figure 1 shows the relative reduction in the design values as a function of number of observations n, for return period, T, equal to 50, 150 and 500 years.

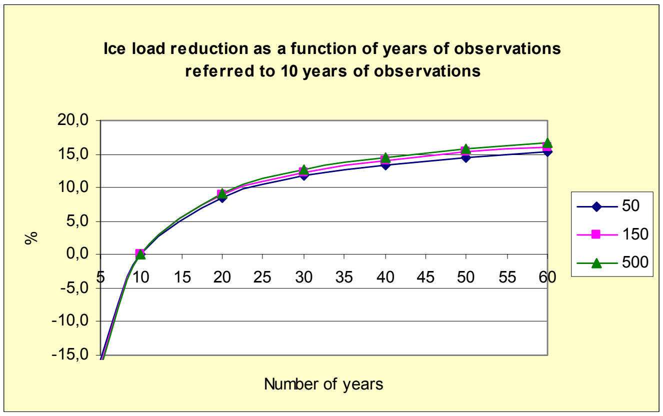

Figure 1. Reduction in design ice loads as a function of number of observation years referred to 10 years.

Table 2 and the curves in Figure 1 show that the effect of increasing the number of years with observations is largest for the fewest number of years with observations. An increase of observations from 5 to 10 years will lead to an ice load reduction of about 14% while the corresponding reduction by increasing the observations from 55 to 60 years only is about 0,5%. This increase can be simply explained as follows: When statistics are based on a large number of data, the prediction of, say a 50 year load, will be more precise than if the same was based on a reduced number of data. The above equation No 9 attempts to compensate the reduced number of years of data by increasing the predicted 50-year load.The shape of the curves in Figure 1 shows that the larger part of the uncertainty is eliminated after 30 years of observations. If the number of observation years is increased from 5 to an infinite number of years the total reduction of the design ice load is roughly 30%. Figure 1 reveals that if you have made observations for 10 years, another 10 years of observations will reduce the design load nearly 10%. An increase from 20 to 30 years of observations will reduce the design loads with further about 3 %.

B. Wind loads

The average value and standard deviation for the 29 annual maximum wind speed values are considerably lower than for the ice loads.Following the same procedure as for ice, the wind speed with a return period of 50 years is calculated to be 24,7 m/s. If the design wind speed is calculated for different numbers of observations based on *the same fixed average value of 16,1 m/s and standard deviation of 2,8 m/s,* the resulting design loads for a return period of 50, 150 and 500 years are shown in Table 3.

TABLE 3. DESIGN WIND LOADS (M/S) AS FUNCTION OF NUMBER OF OBSERVATION YEARS

Number of years	**C - coefficients**		**Design wind loads [m/s]**		
			Return time T years		
n	**C_1**	**C_2**	**50**	**150**	**500**
5	0,458794	0,792778	28,4	32,4	36,7
10	0,495207	0,949625	26,3	29,6	33,2
20	0,523552	1,062822	25,1	28,1	31,3
30	0,536221	1,112374	24,7	27,5	30,6
40	0,54362	1,141315	24,4	27,2	30,2
50	0,548542	1,160661	24,3	27,0	29,9
60	0,552084	1,174665	24,2	26,9	29,8
100	0,560023	1,206489	23,9	26,5	29,4
200	0,567153	1,235977	23,7	26,3	29,1
300	0,569926	1,247866	23,7	26,2	28,9
400	0,571437	1,254501	23,6	26,1	28,9
500	0,572398	1,2588	23,6	26,1	28,8
Infinite	0,57722	1,28255	23,4	25,9	28,6

In this case the ratio between the design wind values based on only 5 observations and the design wind values based on an infinite number of observations is about 1,25. This is half of the variation for design ice loads, due to the much lower standard deviation for the annual maximum wind speeds.

If 10 observations is again chosen as reference, Figure 2 shows the relative reduction of the design wind values, as a function of number of observations n for return time, T, equal to 50, 150 and 500 years.

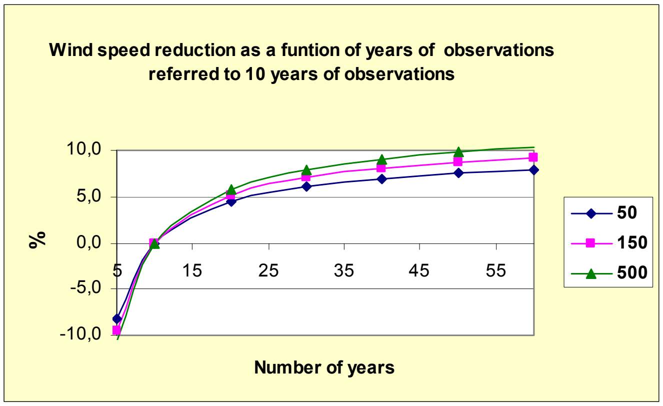

Figure 2. Reduction design wind speed as function of number of observation years referred to 10 years of observations.

If the observations are increased from 10 years to 20 years, the design wind speed will be reduced approximately 5%. If the observation series is increased to 50 years the reduction is in the range of 8 – 10%.

In this case it is observed that the relative reduction by increasing the number of observation years from 30 to 60 years is only giving a reduction of the design wind loads in the range of 2 – 3%.

VI. ECONOMY OF ICE LOAD REGISTRATIONS

Table 4 contains information on the current length and the "as new" cost of the overhead lines at the different voltage levels in Norway. The economical lifetime of the overhead lines is set to 40 years and the marginal cost of ±1 kg ice load per km overhead line corresponds to about 6% of the overall investment cost for a new overhead line. The uncertainty of the existing ice load recommendations in Norway is conservatively estimated to 40%. Based on these assumptions Table 4 also gives information on "price of uncertainty" of the design ice load for different voltage level in Norway.

TABLE 4. TOTAL LENGTH OF OVERHEAD LINES IN NORWAY AND ECONOMIC EFFECTS OF UNCERTAINTIES IN DESIGN ICE LOADS IN US $

Voltage level	< 1	1 - 24	33 - 66	132	300	420	Sum
Total length of OHL [km]	116376	63856	10391	9483	5086	2104	207295
Value as new, [Billion $]	2,82	3,07	1,09	1,44	2,38	1,09	11,88
Annual replacement [km]	2909	1596	260	237	127	53	5182
Annual replacement, [Million $]	70,4	76,7	27,2	36,0	59,5	27,1	296,9
Average ice load [kg]	1,5	3,5	5	5	7	7	-
+/- 40% cost of uncertainty, [Millon $]	2,53	6,44	3,27	4,32	9,99	4,56	31,1

The total "price of the uncertainty" in the design ice loads for the total electric overhead line network in Norway is about 30 million $. This represents about ±10% of the annual replacement value of the grid. If this uncertainty could be reduced by 10% (i.e. from 40% to 36%), this would imply that about 3 million $ less would have been invested in an unknown, and probably in most cases undesired, safety. If the uncertainty in ice loads could be reduced to 20%, the corresponding economic value will be 15 million $. In some cases this would result in somewhat higher annual outage costs. It is obvious that the above economy assumes that the average and standard deviation of ice data remains the same.

In order to have a better coordination of investment costs and maintenance costs in the grid a ice measurement program on existing overhead lines was suggested to the network utilities. The benefit of this would be either

- reduced investment costs if the recommended and highly uncertain design ice loads are to high, or
- the damage to the transmission system and loss of customer supply due to ice storms could be reduced if the recommend design ice value is too low.

It is most likely that the first alternative is more relevant in Norway. The long term experience is that extensive damage and loss of supply during heavy icing periods are quite rare. Table 4 above indicates that to achieve a 10% reduction of the uncertainty the Norwegian utilities could annually spend 3 million $. The fact is that far less is probably needed to achieve such a reduction from where we stand today. Norwegian transmission and distribution utilities are however strongly focused on short term economical results and even small long term investments have low priority. Attempts to initiate such ice monitoring and recording program in Norway have therefore failed.

VII. THE STUDNICE MEASUREMENTS IN THE CZECH REPUBLIC.

All estimates on ice and wind statistics above were based on the assumption of a "constant climate". This means that it would make no difference during which time period wind and ice measurements were taken. In particular, the above estimates of the uncertainties in ice loads were based on this. This assumption will be discussed in this section.

At the mountain Studnice approximately 800 m of altitude in the Czech Republic, ice loads are measured since 1940 and annual maximum ice load continuously recorded. The results from the measurements up to 1998 are given in figure 3 below [3].

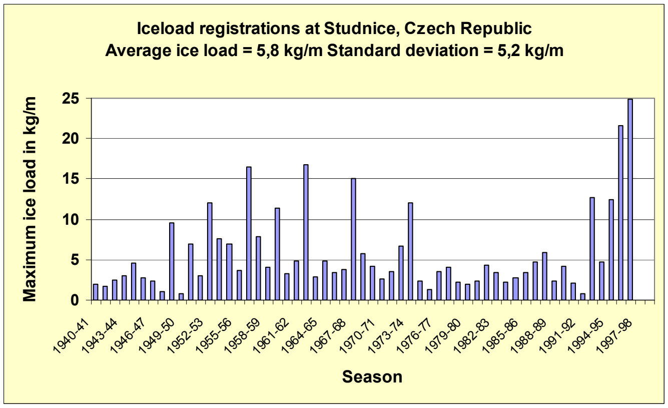

Figure 3. Annual maximum ice load registrations at Studnice.

The average maximum ice load is 5,8 kg/m and the standard deviation is 5,2 kg/m giving a variation factor of 0,9. From these measurements the ice loads with a return period of 50 years are calculated for each period of 10 years by using equation (9) above and corresponding C-factors. In addition the ice loads with a return period of 50 years are calculated for the accumulated period of 10, 20, etc. up 60 years by using equation (9). The result is given in figure 4 below.

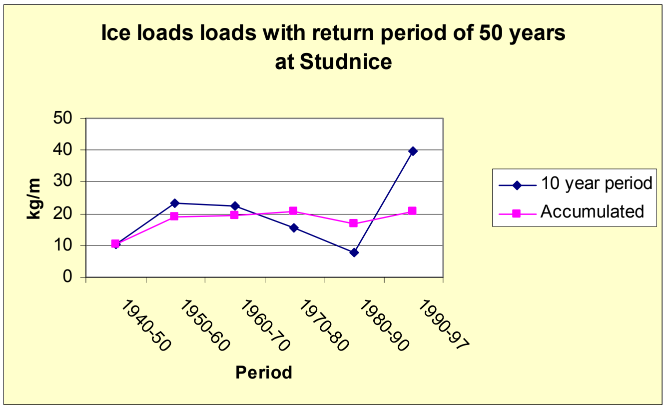

Figure 4. Design ice load for a return period of 50 years based on each separate 10 year period and the total number of years.

As seen in Figure 4, predicting ice loads based on a reduced number of years, such as 10 years, may lead to under- or overdesigning overhead lines.

For example, if the 50 year load prediction was based on the 1980-1990 period, the 50 year ice load would have been near 10 kg/m, while if the 1990-1997 period was selected, the 50 year load would have been 40 kg/m.

If, on the opposite, the total period of ice observations from 1940 to 1997 were selected, the predicted 50 year load would have been 20 kg/m.

The above findings confirm the importance of relying on a long series of climatic data records in order to estimate ice loads corresponding to return periods of 50, 150 or 500 years, particularly in countries where ice loads do not occur every year.

VIII. CONCLUSIONS

The paper addresses the procedure to calculate design weather loads by applying the Gumbel cumulative distribution function as described in IEC 60826. The procedure seems to be adequate for its purpose and it is quite simple to apply. The IEC report also contains curves and tables to further simplify its use.

The chosen example of ice load measurements and records made at Studnice show that the standard deviation of maximum annual ice loads is large (a variation factor in the range of 0,8 to 0,9). Due to this, calculations of design ice loads based on few years of observations may be imprecise. Even simple ice load records may improve the data basis for the calculation of the design ice loads substantially and acquiring such data is very cost effective and highly recommended.

Measurements of wind loads in a coordinated manner are common worldwide and the data basis for the calculation of design wind loads is normally good and much better than the data basis for ice loads.

In all cases there is an economic incentive to measure and collect for a long time ice and wind data for the design of overhead lines. Such long periods of records will provide the best estimates of design ice and wind loads. If the design loads are underestimated due to short periods of data, the failure rate of lines will increase and cause serious economical consequences. If on the other hand, the design loads are overestimated, the initial cost will be much higher and may reduce funds available for other projects.

IX. REFERENCES

[1] IEC 60826 Ed. 3: ”Design criteria of overhead transmission lines”. 2003

[2] CIGRÉ, Technical Brochure 109: Review of IEC 826 "Loading and Strength of Overhead Lines". 1996

[3] CIGRÉ Session 1998. Paper 22-105: “Ice monitoring at stand Studnice. Tuned vibration control of overhead line conductors” F. Popolansky, J. Kruzik, J. Hrabanek, and J. Lago.