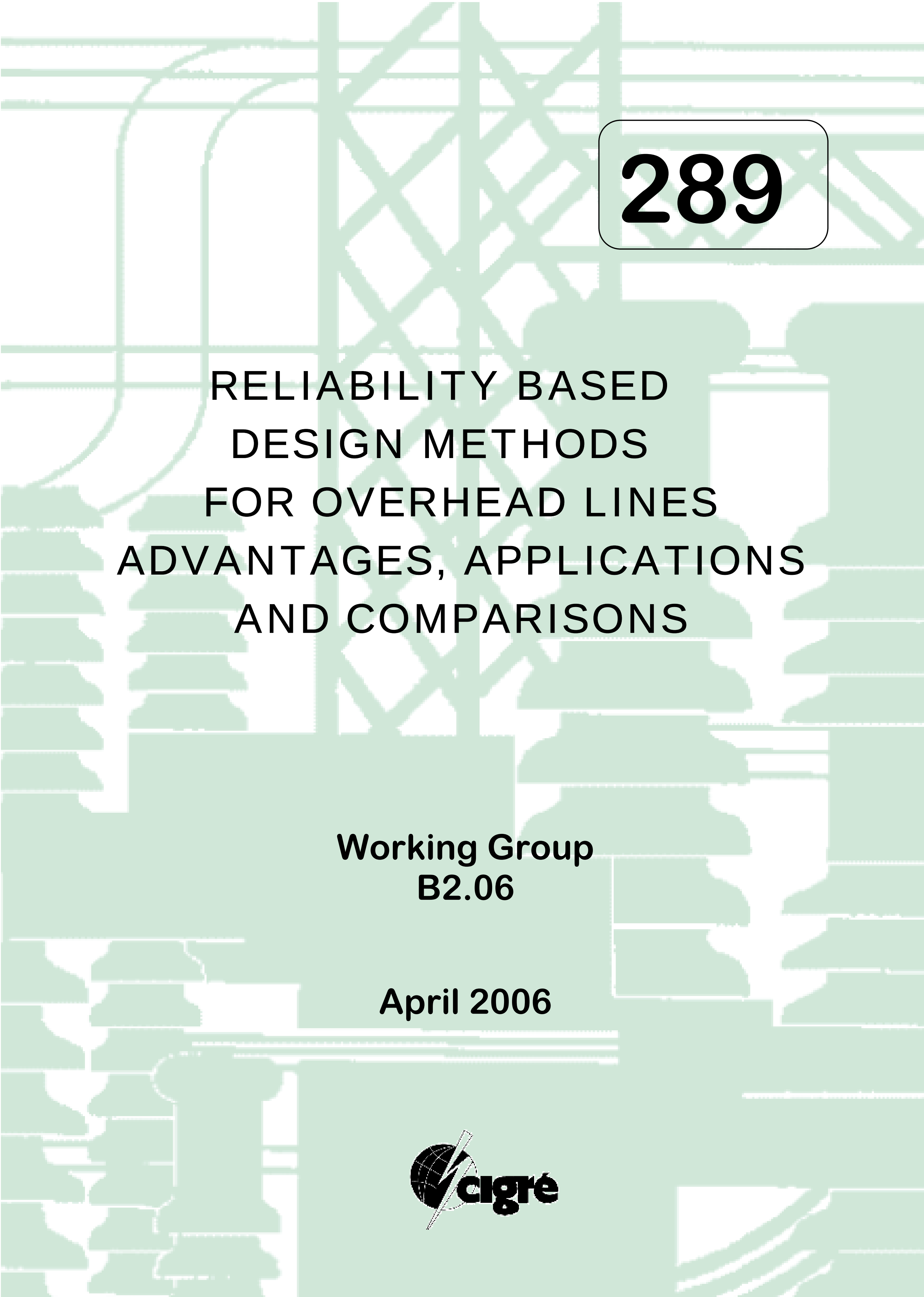

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RELIABILITY BASED DESIGN METHODS FOR OVERHEAD LINES ADVANTAGES, APPLICATIONS AND COMPARISONS

Working Group
B2.06

April 2006

cigré

Reliability Based Design Methods for Overhead Lines Advantages, Applications and Comparisons

Working Group
B2.06

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Reliability Based Design Methods for Overhead Lines
Advantages, Applications and Comparisons

Content of the Technical Brochure

Abstract of the Technical Brochure
Reliability Based Design Methods for Overhead Lines
Advantages, Applications and Comparisons

This Technical Brochure promotes Reliability Based Design (RBD) methods for Overhead Lines and provides recommendations to make Standard IEC 60826 Ed.3, October 2003 and other relevant RBD Codes (ASCE 74, EN 50341) more consistent. Section I summarizes advantages of probabilistic methods over deterministic methods as well as the key features of IEC 60826, and its companion document, CIGRÉ TB No. 178. In Section II possible interpretations of IEC 60826 are clarified by application examples. Section III compares the other RBD Codes with IEC 60826 to assess the significance of any major difference.

Résumé de la Brochure Thématique
Méthodes de Conception Basée sur la Fiabilité pour Lignes Aériennes
Avantages, Applications et Comparaisons

Cette Brochure Thématique valorise les méthodes de Conception Basée sur la Fiabilité pour les Lignes Aériennes et donne des recommandations pour rendre la Norme CEI 60826 Ed.3, octobre 2003 et d’autres Codes relevants (ASCE 74, EN 50341) plus cohérents. La Section I résume les avantages des méthodes probabilistes par rapport aux méthodes déterministes, ainsi que les particularités de la CEI 60826, et de son document d’accompagnement BT CIGRE No. 178. Dans la Section II les interprétations possibles de la Norme sont clarifiées par des exemples d’application. La Section III compare les autres Normes avec la CEI 60826 afin d’évaluer la signification des différences majeures.

Reliability Based Design Methods for Overhead Lines
Advantages, Applications and Comparisons

Content of the Technical Brochure

CIGRE Technical Brochure

Reliability Based Design Methods for Overhead Lines
Advantages, Applications and Comparisons

EXECUTIVE SUMMARY

From Elias Ghannoum, Jan Rogier, Lars Rolfseng, Chris Thorn

Working Group B2.06

April, 2006

Reliability Based Design Methods for Overhead Lines
Advantages, Applications and Comparisons

AIM OF THE TECHNICAL BROCHURE

The Technical Brochure aims to increase understanding of Reliability Based Design (RBD) methods as well as their application to Overhead Lines for the calculation of loadings and strength of line components.

Section I demonstrates why probabilistic methods constitute a major improvement compared to deterministic methods. It summarizes the main features of International Standard IEC 60826 Ed. 3 (October 2003) and its companion document, CIGRÉ Technical Brochure No. 178 (February 2001).

The scope of Section II is to clarify the interpretations of IEC 60826 and to recommend amendments by providing an application example based on one given set of input parameters already used in CIGRE Technical Brochure No. 109 (1996) for calculations based on the previous Technical Report IEC 826 (1991).

The scope of Section III is to compare other RBD Codes (ASCE, EN) with IEC 60826 and to assess the level of consistency and the significance of any major difference.

Key-words: Design, Overhead Line, Reliability, Security, Safety, Return Period, Load, Strength, Wind, Wind Speed, Ice, Support, Tower, Conductor.

BUT DE LA BROCHURE THEMATIQUE

La Brochure Thématique a comme objectif d’augmenter la compréhension des méthodes de Conception Basée sur la Fiabilité (RBD), ainsi que leur application aux Lignes Aériennes pour le calcul des charges et de la résistance des composants de ligne.

La Section I démontre pourquoi les méthodes probabilistes constituent une amélioration majeure par rapport aux méthodes déterministes. Elle résume les aspects principaux de la Norme Internationale CEI 60826 Ed. 3 (octobre 2003) et de son document d’accompagnement, la Brochure Thématique CIGRÉ No. 178 (février 2001).

Le but de la Section II est de clarifier les interprétations de la CEI 60826 et de recommander des amendements en fournissant un exemple d’application, basé sur une série de données déjà utilisées dans la Brochure Thématique CIGRE No. 109 (1996) pour les calculs suivant l’ancien Rapport Technique CEI 826 (1991).

Le but de la Section III est de comparer d’autres Codes RBD (ASCE, EN) avec CEI 60826 et d’évaluer le niveau de cohérence et le sens de toute différence majeure.

Mots-clefs: Conception, Ligne Aérienne, Fiabilité, Sûreté, Sécurité, Période de Retour, Charge, Résistance, Vent, Vitesse de Vent, Givre, Support, Pylône, Conducteur.

Reliability Based Design Methods for Overhead Lines Advantages, Applications and Comparisons

Executive Summary

GENERAL INTRODUCTION

This Technical Brochure aims to increase understanding of International Standard IEC 60826 “Design Criteria of Overhead Transmission Lines”. It demonstrates why Reliability Based Design (RBD) methods constitute a major improvement compared to deterministic methods. The main features of IEC 60826 are summarized.

Possible interpretations of IEC 60826 are clarified by application examples. Some recommendations are given to improve the International Standard.

Finally, some other RBD Codes (EN 50341, ASCE 74, NESC) are compared with IEC 60826 to assess the level of consistency and the significance of any major difference.

THE NEED FOR RELIABILITY BASED DESIGN IN OVERHEAD LINE DESIGN

Many current standards and design practices in the world are deterministic in nature. Some of them are even imported from other countries, despite major differences in climatic and terrain conditions.

Some of the potential deficiencies of deterministic methods are given hereafter and practical examples are provided in Section I of the Technical Brochure.

Possible inconsistencies and unbalance in strengths of components

The objective of deterministic methods is to comply, as a minimum, with the safety or overload factors required for each loading case specified. There are usually no requirements for a preferred sequence of failure.

Unknown reliability level

Except by a general inference from very long experience, it is very difficult to attribute a reliability level to any design based on deterministic principles. They do not even recognize that load can exceed strength. Both values are deemed to be constant. Moreover, many components are over-designed, while the line reliability is determined by the weakest component. Such heterogeneous design leads to uneconomical solutions.

Difficulty to adjust the overall line reliability

A designer who wants to increase the reliability of a given line because of its importance in the network has very few means to assess the significance of increase in the safety factors, say of 10% or 30%.

Difficulty to design heterogeneous structures

If the same safety factors are applied to loads on materials with different strength dispersion such as compressive strength for wood poles and steel cross-arms, they will lead to unequal reliability level between these structural parts of the same structure.

Difficulty to adjust design to local weather conditions

Deterministic methods cannot efficiently cope with the variations in weather loading that occur in the service area.

CASE STUDIES OF INCONSISTENCIES IN DETERMINISTIC DESIGN APPROACHES

Use of constant wind speed/pressure on conductors

In many deterministic standards, wind speed is specified as a constant value to be applied to all conductors and earth wire. Many of these standards do not provide for adjustment due to height above ground level or terrain category (ground roughness). Furthermore such wind pressure may not even vary within a very large geographical area.

This Technical Brochure provides a typical calculation example where the impact of the above deterministic assumption on the reliability has been assessed. A Low Voltage (LV) has been compared with an Extra High Voltage (EHV) line with conductors respectively at 10 m and 30 m height. It is obvious that the line reliability is not the same as a constant wind pressure on conductors has been considered. If both lines were built for the same reliability level (same reference wind speed at 10 m height), the adjusted wind speed ratio becomes 0.88 for LV to EHV lines. In the deterministic design approach the wind speed on the higher EHV is underestimated with a factor 0.88. If the LV line has been designed for a return period T = 50 years, then the equivalent return period of the EHV line would be in the range of only 10 years (see Figure 1). Similarly, if the EHV line were designed for a reliability level of 50 years, the corresponding reliability level of the LV line would be about 250 years.

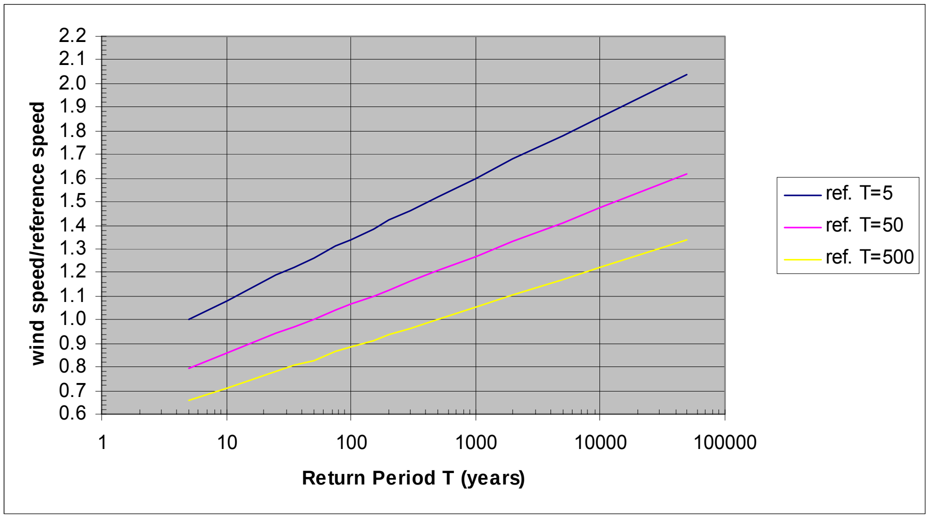

Figure 1 - Variation of wind speed with the return period

Improper application of tower safety factors for foundation design

When safety factors are applied to all forces for which towers are designed, the calculated foundation reactions can be erroneous. In presence of wind loads, increasing the dead weight of the tower and the conductors, which is practically invariable, leads to underestimating the critical uplift loads on foundations while over estimating less critical compressive loads.

Inability to integrate quality in the design process

In deterministic design, load and strength are expressed using one value, either specified by the applicable codes or standards or derived from experience. This value is usually named “nominal”, characteristic, or guaranteed load or strength.

This Technical Brochure provides an example where the most reliable product to be used in a transmission line has the least strength dispersion, despite the fact that its average strength is lower than the others. Reduction of scatter in strength is obviously a sign of quality.

Mismatch between line components

Irrespective of the design approach, it is commonly accepted that tension towers should be designed more reliable than suspension towers. In deterministic design approaches, this translates in using larger safety factors for tension towers. However, this treatment may not be sufficient to guarantee this objective, particularly when suspension towers are used at a fraction of their maximum spans.

HOW RBD METHODS ADDRESS THE DEFICIENCIES OF DETERMINISTIC DESIGN PROCEDURES

The following basic principles are used by RBD methods in order to address the deficiencies stated above in deterministic methods.

Limit loads are specified

Contrary to deterministic methods that incorporate safety and/or overload factors, RBD specifies the limit loads that each line component has to withstand without damage.

Loads and strengths are recognized as random variables

When the randomness of loads and strengths are taken into account, there is an immediate recognition that absolute reliability cannot be achieved. Therefore, RBD design standards will have to specify an acceptable maximum probability of failure.

Design loads are selected based on the required return period

It is widely accepted that yearly maximum climatic loads such as ice and/or wind, follow extreme distribution functions. With such statistical functions, designers can associate a value of loads for any selected return period.

The characteristic strength is also dependent on strength dispersion

Similarly, the strength is also a random variable, typically described by normal or log-normal distribution functions. The design strength is chosen with an exclusion limit of 2 to 10%.

Basic design equation

The line reliability threshold corresponds to the condition where the climatic load effect is equal to the design strength. If load does not exceed strength, then the transmission line is reliable.

HOW TO APPLY IEC 60826

Design requirements

The design according to IEC 60826 [1] originates from the following requirements:

- Reliability: These requirements consist of climatic loads (wind, ice, temperature and their combinations) and aim to provide lines with satisfactory service performance. Statistical tools are used to quantify these loads. The basic design equation is discussed in the Technical Brochure.
- Security: These requirements relate to behavior of lines once failure is initiated. They aim to prevent uncontrolled propagation of failures or cascading.

- Safety: These requirements aim to prevent human injury. They consist of construction and maintenance loads.

Three reliability levels (I, II, III) are provided in IEC 60826. These levels correspond to return periods of climatic design loads of 50, 150 and 500 years. It is aimed that the risk of failure under security and safety loads should be very low. They are deterministic concepts, while reliability is probabilistic.

<u>Design steps of IEC 60826</u>

The design methodology as per IEC 60826 can be summarized in Figure 2. It is noted that activities (a) and (h) listed in this figure are not within the scope of IEC 60826.

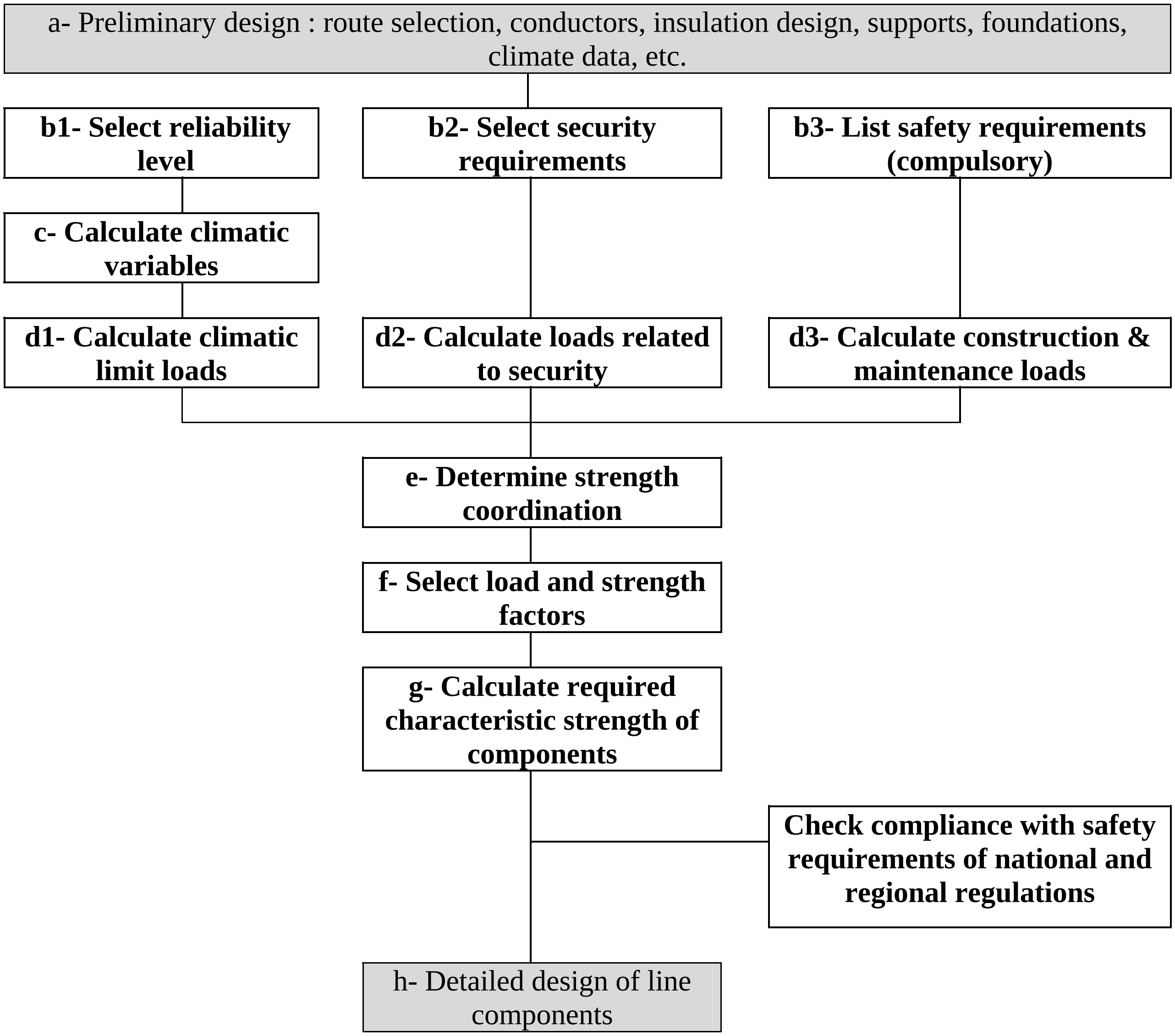

Figure 2 - Transmission line design methodology according to IEC 60826

Difference between theoretical and actual reliability

IEC 60826 recognizes that the actual reliability may differ from the theoretical reliability when load and/or strength factors such the ones listed below are not properly accounted for:

- The actual use factor of components is quite different from the assumed value of 1.0 (particularly for suspension towers where it is virtually equal to the ratio of actual to maximum design wind/weight span);
- Direction of wind speed in relation to that of the line;
- Exclusion limit of strength different from the assumed 10%;
- Number of components subjected to maximum load intensity;
- Quality control during fabrication and construction.

Methods to take into account the above factors are covered in the subject standard.

Strength coordination

In IEC 60826, line components can be designed to fail in a preferred mode (with a 90% probability) called “preferred sequence of failure”. The best (or least damaging) failure mode is the one where the consequences of the first failure on the line are minimized. Strength factors allowing to target a preferred sequence of failure are provided in the standard.

Wind loads

Methods to calculate wind forces, starting with a reference wind speed, are provided in the standard. For the purpose of calculating wind pressure and forces, four categories of ground roughness, also called terrain categories, are provided:

- A- Flat coastal areas and deserts;
- B- Open country, cultivated fields;
- C- Numerous low height obstacles;
- D- Suburban areas.

The reference wind velocity V_{RB} considered in IEC 60826 consists of a 10 min average, at 10 m height, in a terrain type B. The standard provides for conversion from other wind data, having different averages or located in a different terrain category, to the above reference value.

The conversion from wind speed to forces on line components takes account of:

- Terrain category;
- Height factor;
- Span factor;
- Gust response factor;
- Shape factor.

Ice loads

Ice accretion on conductors and structures is the source of important loads, and often controls the design in many northern countries. The standard covers three types of ice accretion: precipitation glaze icing, wet snow and in-cloud rime icing. Methods to calculate design ice loads are provided and cover a range of cases with various availabilities of statistical data.

Combined ice loads with wind

The presence of wind during or after icing episodes requires special loading cases. The calculation of combined forces due to wind on ice covered conductors is provided in the standard and takes into account: the ice thickness or ice weight per unit length of conductor, ice density, wind speed during icing, and drag coefficient of ice covered conductor.

CONTINUITY OF SERVICE

It should be noted that increasing reliability (upgrading) is not the only way to improve continuity of service of overhead lines. Overall costs are not so much determined by the probability of failure, but rather by the possible consequences of failure, including the uncontrollable propagation of failures, that may extend well beyond an initial failure. Those consequences can be reduced significantly by the following cost-effective measures:

- Proactive solutions, such as:
    - Strength coordination;
    - Application of torsional and longitudinal tower strength due to broken conductors;
    - Load control devices;
    - Anti-cascading towers;
    - De-icing methods;
    - Construction of other overhead lines and underground cables, etc.;

- Reactive solutions, such as:
    - Emergency restoration structures;
    - Training of linemen, etc.

The reference return period of 50 years or the annual probability of line failure of 2.10^{-2} is acceptable in respect of safety of the public, because the combined probability with human accident is very low (2.10^{-7} per man year according to the French experience). This probability is comparable with risks for transportation by airplane or by train (from 10^{-7} to 10^{-6} per man year). Moreover, as components are usually designed by families and not individually, because they are designed prior to specific knowledge of the real line parameters, the use factor finally increases the actual line reliability.

The reference reliability level is generally regarded as providing an acceptable reliability level in respect of continuity of service and safety of the public.

APPLICATION EXAMPLE OF IEC 60826

Purpose of the application example

The scope of Section II of the TB is to clarify the interpretations of IEC 60826 (2003) [1] and to review the application example of CIGRE Technical Brochure 109 (1996) [2], issued by CIGRE on behalf of WG B2.06.

Calculations

The calculations were carried out in different steps:

- Assessment of the technical and meteorological data;
- Conversion of reference wind data in terrain category B to terrain category C of the line;
- Calculation of loads on conductors and earth wires of a line section of 15 towers, already used in the above mentioned application example of TB 109;
- Calculation of loads on some selected towers by means of a line calculation program: a tangent tower and an angle tower, both with a suspension insulator set and an angle tower with strain insulator sets;
- Comparison of the new longitudinal, vertical and transversal forces (according to IEC 60826) with the forces in TB 109 (according to IEC Technical Report 826), in relative and absolute values.

For the case of ice loading, two calculations were performed based on:

- The full statistical information over 12 years;
- The knowledge of only the highest (overall) load in 12 years.

The calculations of wind loads according to IEC 60826 (2003) and IEC TR 826 (1991) are consistent with insignificant load differences on conductors and towers. The largest differences occur for ice loads mainly due to the fact that ice accretions increase with the height for precipitation ice. The calculations reveal that the improved description of ice loads in IEC 60826 is important and that proper quality ice measurements combined with development of ice models are important in regions exposed to atmospheric icing.

Recommendations

Specific recommendations are provided in Section II of the Technical Brochure in order to propose clarifications and changes to some clauses of IEC 60826. Section II will officially be forwarded to IEC/TC11 for follow-up actions of the Standard.

COMPARISON WITH OTHER RBD CODES

Purpose of the comparison

Since the publication of IEC TR 826 in 1991, some Overhead Line design Codes based on RBD principles have been published. These documents have generally adopted many of the concepts given in IEC TR 826, but there are also some substantial differences.

The purpose of Section III is to compare the methods adopted for the calculation of mechanical loadings for overhead power lines according to these design Codes with IEC 60826. The main objective is to assess the level of consistency and the significance of any major differences between the different Codes.

IEC 60826 [1] is compared with CIGRE TB 178 [3], the European CENELEC Standard EN 50341-1 [4], the latest April 2005 draft of the North American Standard ASCE 74 [5] and the Safety Standard NESC 2002 [6].

Overview of the comparison

All the Codes considered share many common features. All adopt a RBD method for calculation of climatic loads, essentially similar to IEC 60826. However, the European Standard EN 50341-1 also provides a deterministic “Empirical Approach” adopted by some countries.

Climatic loadings tend to be the most important in the probabilistic design of overhead lines. They are always based on weather events of a reference return period, usually 50 years. All Codes contain guidance on security and safety loadings.

The range of loading cases considered differs between the various Codes, with IEC offering the most extensive range.

IEC takes a reference wind speed based on a 10 minutes average, whereas ASCE/NESC adopt a 3 second gust wind speed. EN considers both options.

The wind model also differs between the Codes. For the purpose of the comparison the variation of wind speed with terrain category and height above ground, the original equations have been converted and split into two parts. All Codes apply a power law for the height variation, except the European Standard EN that applies a logarithmic law.

There are minor differences in the formulation of the basic design equations. However IEC is the only standard where the impact of height above ground on wind speed is combined with the gust response factor in a combined wind factor.

Formulas are also compared for effective wind pressure on conductors and lattice towers, including the effects of terrain category, drag coefficient and gust factors. There are fairly small differences for the span reduction factor between IEC/CIGRE and EN, but ASCE varies significantly from the other documents.

IEC provides statistical methods to achieve strength co-ordination between the least reliable components and ASCE provides appropriate strength levels for relative reliability. There is only general guidance given in EN and no explicit mention of this subject in NESC.

This Technical Brochure provides many synthetic tables in order to compare symbols, terms, definitions and values for the different Codes.

Particular comparison between IEC, ASCE and some National Normative Aspects of EN 50341-3

The Appendix to Section III of the TB gives a comparison between conductor wind pressures, including gust, height and span related effects for wind spans varying from 200-600 m and mean heights of 10 m, 30 m, and 50 m above ground in Terrain type B to IEC. This information is given in graphical form in Figure 3 for conductor height 30 m. It is shown that IEC/CIGRE and the Main Body of EN agree fairly closely, but ASCE gives significantly lower values than either of the other documents. The main reason for this is believed to be the use of the simplified Davenport gust response model. It may be noted that the use of the full Davenport model is allowed as an option in ASCE, and this gives results much closer to IEC.

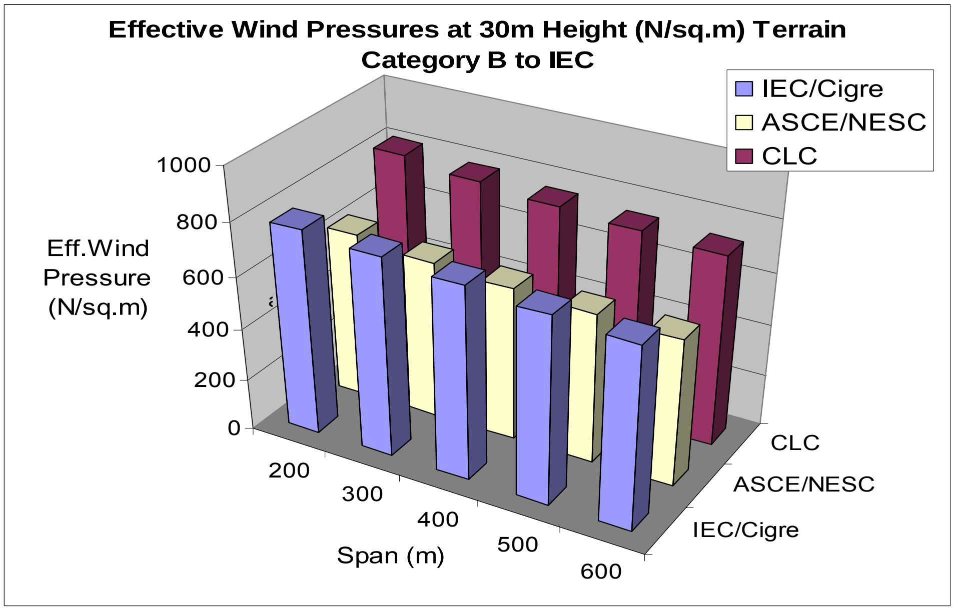

Fig 3. - Comparison of Effective Wind Pressure for IEC/CIGRE, ASCE/NESC and EN (CLC) for various spans and height 30 m above ground for IEC Terrain Category B

The conductor wind loadings calculated in accordance with the CENELEC National Normative Aspects (NNA) for various European countries are compared with IEC/CIGRE, the Main Body of EN and ASCE.

GENERAL CONCLUSION

Section I of the Technical Brochure summarizes advantages of Reliability Based Design (RBD) methods over common deterministic based methods as well as the key features of Standard IEC 60826 and its companion document, CIGRÉ Technical Brochure No. 178.

Section II clarifies interpretations of IEC 60826 by application examples.

Section III compares some other RBD Codes (ASCE 74, NESC, EN 50341) with IEC 60826 to assess the significance of any major difference.

This Technical Brochure promotes RBD methods for Overhead Lines and provides recommendations to make IEC 60826 and other relevant RBD Codes more consistent.

REFERENCES

[1] IEC 60826 - Ed. 3.0 (October 2003): “Design Criteria of Overhead Transmission Lines”

[2] CIGRÉ WG 22.06, (Dec. 1996), "Review of IEC 826 – Loading and Strength of Overhead Lines", Technical Brochure 109

[3] CIGRÉ WG 22.06, (Feb. 2001), "Probabilistic Design of Overhead Transmission Lines", Technical Brochure 178

[4] EN 50341-1:2001 - Overhead electrical lines exceeding AC 45 kV – Part 1: General requirements - Common specifications

[5] ASCE 74 - Guidelines for transmission lines structural loading: Draft as of April 2005

[6] NESC 2002 - National Electrical Safety Code 2002

CIGRE Technical Brochure

Reliability Based Design Methods for Overhead Lines
Advantages, Applications and Comparisons

SECTION I - ADVANTAGES

Prepared by Elias Ghannoum
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Working Group B2.06

April, 2006

Working Group B2.06 “Principles of Overhead Line Design”

TECHNICAL MEETING OF CIGRE B2 COMMITTEE - PARIS, FRANCE

Section I - TUTORIAL
September 2004

Reliability Based Design of Overhead Transmission Lines According to IEC 60826 and CIGRÉ TB 178-Why you need it, and how to use it

Prepared by Elias Ghannoum, on behalf of CIGRÉ Working Group B2-06[1]

1. INTRODUCTION OF SECTION I

During the last decades, the IEC (International Electrotechnical Commission) Committee TC11 and CIGRE Study Committee SC 22 (now SC B2) pioneered improvement of overhead transmission lines design criteria as well as the introduction of reliability/probability based design concepts, refer to CIGRÉ 1990 [2], CIGRÉ 2001 [3], Ghannoum-Orawski, 1986 [4], etc.

The technical work on reliability based transmission line design started in CIGRÉ more than 40 years ago under the hospices of Study Committee 22. Many experts, to name a few, such as Commellini, Manuzio, Cojan, Paris, Schjetne, Wood, Orawski, Kieβling, Henrioul, Rogier, Ghannoum, etc., contributed to this work either in the SC 22 or in CIGRÉ papers and publications.

Further technical development was pioneered by a joint effort between CIGRÉ and IEC through both technical working groups SC22-WG06 from CIGRÉ, initially chaired by Georges Orawski from the UK, and IEC/TC11/WG08 chaired by Elias Ghannoum from Canada.

As a result of the above technical work, a milestone occurred in 1991 when the IEC 826[2] entitled "Loading and Strength of Overhead Lines” was published by IEC in 1991 as a Technical Report type 2, i.e., a pre-standard document to be reviewed in a few years for the purpose of converting it to an IEC standard. This publication introduced reliability and probabilistic concepts for calculation of loading and strength requirements for overhead lines components.

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[1] *Current Members of SC B2-WG-06: Joël ANGELINI, Pavel FRONEK (secretary), Elias GHANNOUM (Former Convenor), Tip GOODWIN, Angel GALLEGO, Friedrich KIESSLING, Ghyslaine McCLURE, João Felix NOLASCO, Krzysztof PUT, Oswaldo REGIS Jr., Jan ROGIER (Convenor), Lars ROLFSENG, Sava Skrobonja, Chris THORN, D CHOUDHRY, Svein FIKKE, Asim HALDAR, Sven HOFFMANN, Trevor E JACOBS, Yuji KUBOTA, Robert LAKE, Pierre MARAIS, Dzevad MUFTIC, Pekka RIISIO, Helmut STRUB, Sergey TURBIN, Brian WAREING, Patrick ZHAO. The contribution of these previous members of WG06 is also recognized: Kare SCHJETNE, Friedrich KIESSLING, Georges HENRIOUL, Jacques PEZARD, Tony PLOEG, Paul DE WECK, Joe POHLMAN.*

[2] *The new number of this publication in the IEC catalogue is 60826*

Subsequent work by CIGRÉ SC22-WG06 helped modifying the IEC report and, in October 2003, Standard IEC 60826 [1] was published by the IEC after a unanimous positive vote by National Committees.

This paper aims to increase understanding of IEC 60826 as well as its application to Overhead Lines. It demonstrates why Reliability Based Design (RBD) methods constitute a major improvement compared to deterministic methods and summarizes the main features of IEC 60826.

2. THE NEED FOR RELIABILITY BASED DESIGN IN OVERHEAD LINE DESIGN

Many current standards and design practices in the world are deterministic in nature. Some of them are even imported from other countries, despite major differences in climatic and terrain conditions.

However, it is fair to recognize that deterministic methods have evolved, and many utilities or countries tried to address some deficiencies they have identified in their deterministic design practices by specifying additional loading cases and strength requirements, often much more critical than their basic standards.

Experience and technical studies have shown that deterministic methods have inherent deficiencies that cannot be addressed by minor changes in the design requirements, and can only be resolved by migrating to RBD. Some of the potential deficiencies of deterministic methods are given hereafter and practical examples are provided.

2.1. Possible inconsistencies and unbalance in strengths of components

The objective of deterministic methods is to comply, as a minimum, with the safety (or overload) factors required for each loading case specified. There are usually no requirements for a preferred sequence of failure in these standards and any sequence can be expected as a result of deterministic design.

In a number of reviews of standards and line failure analyses performed by the Author, it was found that the withstand of some angle and dead-end towers were in fact less than that of tangent towers. This is particularly true in lines located in icing areas where tangent towers are designed with wind and weight spans significantly exceeding average spans, and angle towers used at their maximum angles[3].

Cases where tangent tower can withstand as much as 40-50 mm of radial ice, while angle towers can fail due to 35 mm of ice are not uncommon in locations with important ice loads.

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[3] *This is usually the case in many lines, because line routes and P.I. angles often aim to use expensive angle towers at their maximum angles.*

2.2. Unknown reliability level

Except by a general inference from very long experience, it is very difficult to attribute a reliability value to any design based on deterministic principles. In fact these principles do not even recognize that load can exceed strength (both values are deemed to be constant) and often imply that whoever follows such principles should obtain a safe and reliable line.

The past experience is not always a good descriptor of reliability, especially if the experience with these design criteria is not long enough and the transmission line system covers only a small fraction of the total service area. For example, if the real probability of failure of existing lines designed according to deterministic loads is low, say 3% every year, there is about 50% chance that no failure will occur during a 20-25 year life span. Thus, the fact that no failures occurred during this period is not always a good measure of the actual line reliability.

2.3. Difficulty to adjust the overall line reliability

If a designer wants to increase the reliability of a given line because of its importance in the network, he has few means to assess the quantum of increase in the safety (or overload) factors he currently uses to improve the reliability. He simply does not have sufficient information to decide if an increase, say of 10% or 30% in the safety factors, would be significant enough or not.

2.4. Difficulty to design heterogeneous structures ex. (steel and wood)

When designing a structure using different materials, such wood poles and steel crossarms, if the same overload factors are applied to loads, they will lead to unequal reliability between these structural parts of the same structure.

For example, the compressive stresses of wood pole stresses in North America were given as average values. In recognition of this fact and the large strength dispersion of wood strength, a safety factor of 4 was specified for compression loads. If a wood crossarm is substituted by a steel section, the deterministic design methods do not have the appropriate tools to provide for a substitute and equivalent safety factor for steel crossarms.

2.5. Difficulty to evolve with new technologies

The above example of a structure involving different material can be extended to a more general issue of the equivalence between safety factors/overload factors to be applied to different structural components. For example, steel and concrete pole manufacturers recently challenged the large safety factors imposed on them by standards in North America arguing that steel pole properties are quite predictable contrary to wood poles.

The same could be extended to new types of materials such as poles made of fiber reinforced concrete or fiberglass, etc. Deterministic methods cannot provide designers with reliable guidelines to establish equivalent requirements between new material technologies and established ones.

2.6. Difficulty to adjust design to local conditions

Deterministic methods cannot efficiently cope with the variations in weather loading that occur in a service area. For example, not so long ago, North America was divided in only a handful of loading zones, each one as large as many European countries combined together. Another major problem arises because the specified climatic loadings are not related to any specified return period. For example, the combined ice and wind load of 12.7 mm of radial ice and 385 Pa of wind pressure[4] specified in CSA C22.3 for Canada was estimated, using RBD, to correspond to return periods of 3 to 500 years, depending on the actual location.

3. CASE STUDIES OF INCONSISTENCIES IN DETERMINISTIC DESIGN APPROACHES

3.1. Use of constant wind speed/pressure on conductors

In many deterministic standards, wind speed is specified as a constant value to be applied to all cables (conductors and GW). Many of these standards do not provide for adjustment due to height or terrain type (roughness). Furthermore, such wind pressure may not even vary within a very large geographical area.

Let us try to assess the impact of the above deterministic assumption on reliability: Assume a hypothetical deterministic standard that specifies a constant wind pressure on conductors of 500 Pa and a safety factor of 2. The corresponding limit wind pressure, assuming a linear behavior of the tower, is thus 1000 Pa. If this wind pressure is used to design a low voltage line with conductors at 10 m height, and another Extra High Voltage (EHV) line with conductors at 30 m height, it is obvious that the reliability of the two lines will not be the same. More disturbing is the fact that the resulting reliability of the low voltage line will end up much higher than the reliability of the EHV line.

In order to quantify the reliability of each line, we need to look at the variation of wind speed with height. If these lines are located in a terrain type B, the wind speed increases according to equation: $V_{30m} = V_{10m} (30/10)^{1/7}$, which leads to $V_{30m} / V_{10m} = 1.17$. Since wind pressure is proportional to the square of wind speeds, the design wind pressure on the conductors for both lines should correspond to a ratio of 1.37 if they were designed for the same reference wind speed (or the same reliability). Since the low voltage line is usually built with small spans, say of 100-200 m compared to about 400 m for the EHV line, the latter will see reduced wind pressure of 0.94 due to the span effect[5]. The adjusted wind speed ratio becomes 1.37 x 0.94= 1.29 and the ratio of wind speeds become $(1.29)^{1/2} = 1.14$.

The assessment of the ratios of reliabilities, expressed in terms of the return period (T) of design loads can be done if it is assumed that both lines are designed according the same characteristic strength of $R_{10\%}$.

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[4] *This pressure corresponds to a 10 min wind speed of about 65 to 70 km/h for conductors at 10 m of height in a terrain type B.*

[5] *Figure 4 of IEC 60826 standard*

For example if the wind pressure of 1000 Pa at 10 m of height (case of the low voltage line) corresponds to 50 year return period, then the equivalent return period of a wind pressure of 775 Pa (1000/1.29) for the EHV line would be in the range of 10 years (see Figure 1). Similarly, if the EHV line were designed for a reliability level of 50 years, the corresponding reliability level of the low voltage line would be about 250 years.

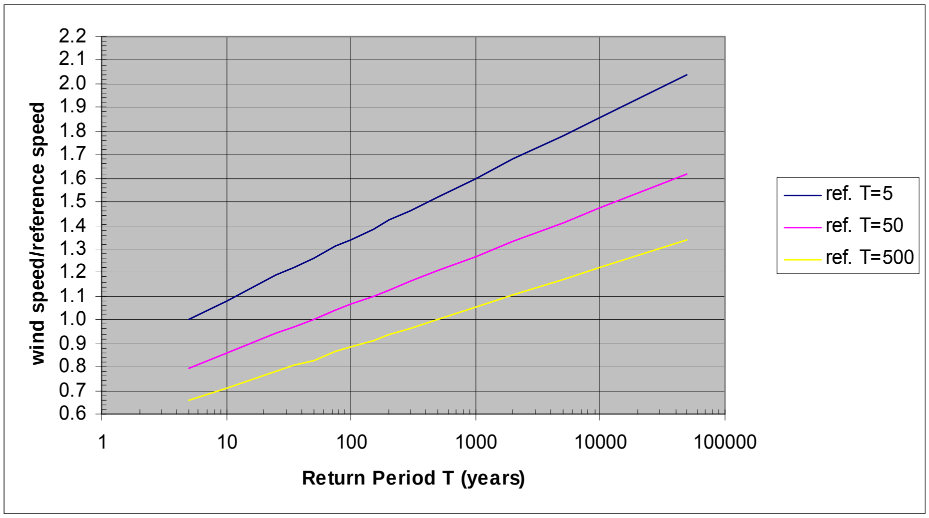

Figure 1 - Variation of wind speed with the return period

3.2. Mismatch between design strength and clearances

In many deterministic approaches, the structures are designed for a specified load multiplied by a load factor or, in some cases, the specified loads are compared to stresses divided by a safety factor. In both cases, clearances above ground and obstacles are usually checked under the maximum temperature, and occasionally, under the weather load case that will yield the largest sag.

Assume a line in an ice loading area where the specified ice load is 20 mm of ice (density 0.9) in a deterministic design standard that imposes a load factor of 2.5. Using a Condor conductor data (diameter = 27.8 mm and unit weight = 15.9 N/m), the unit weight of the ice covered conductor becomes 41.4 N/m. With the overload factor of 2.5, the conductor unit weight becomes 103.5 N/m, a value that corresponds to a limit radial ice thickness of 4.43 cm.

Table 1 - Variation of conductor sag (m) with weather conditions of a 400 m span		
Weather condition	**Stringing parameter[6] at 20 °C, final condition**	
	1500 m	**2000 m**
60 °C	14.8	11.7
80 °C	15.6	12.6
2 cm radial ice	15.0	12.5
4.43 cm radial ice	20.8	19.2

In Table 1 we have compared the conductor sags at elevated temperatures of 60 and 80 ^{o}C with sags due to a deterministic ice load of 2 cm and its equivalent limit load of 4.43 cm. As noted from this table, the sags at 4.43 cm of ice are substantially larger than the elevated temperature sags. Thus it can be concluded, using the above example, that the deterministic design procedure will provide towers with strength capable to withstand 4.43 cm of radial ice, but the line will seriously infringe ground clearances by as much as 5.2 to 6.6 meters if such ice load were to occur.

3.3. Improper application of tower safety factors for foundation design

When safety factors are applied to stresses, or when overload factors are applied to all forces for which towers are designed, the calculated foundation reactions can be erroneous.

For example, assume that a design standard calls for a safety factor of two to be applied to steel stresses. This approach is roughly equivalent to multiplying all tower loads by 2, including the dead weight of the tower and of the conductors, both of which are practically invariable. In presence of wind loads, increasing the dead weight leads to underestimating the critical uplift loads on foundations while over estimating less critical compressive loads[7].

For example, assuming that the dead load from the tower and the conductor is 50 kN per leg and the overturning wind moment applies 150 kN per uplift or compression leg. The total compressive load is thus 200 kN per leg and 100 kN for the uplift leg. A safety factor of 2 will imply the design of the compressive legs for 400 kN and the uplift legs for 200 kN.

Bearing in mind that the dead loads are relatively constant compared to wind loads, let us now calculate the uplift and compression loads assuming that the safety factor of 2 is applied only on wind loads.

The compression leg will now need to be designed for 2 (SF) x 150 kN (wind) + 50 (dead load) = 350 kN, while the uplift leg will be designed for 2 (SF) x 150 kN (wind) – 50 (dead load) = 250 kN. These results contrast with the previous ones where the foundation reactions were 400 kN and 300 kN respectively.

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[6] *The catenary parameter is equal to the horizontal tension divided by the unit weight of the conductor*

[7] *The opposite situation occurs for the tower main legs, where the compression forces will be overestimated and the tension forces underestimated.*

This problem does not occur in RBD because the latter uses un-factored limit loads. Consequently, dead loads will not be artificially amplified as the case with many deterministic methods.

3.4. Inability to integrate quality in the design process

In deterministic design, load and strength are expressed using one value, either specified by the applicable codes or standards or derived from experience. These values are usually named “nominal”, characteristic, or guaranteed loads or strengths. In real life, the strength of any component is not constant, but represents one point in the strength density function.

Let us assume that we have a choice between three insulator manufacturers all of them offering an insulator with a guaranteed strength of a 160 kN corresponding to a 10% exclusion limit. In deterministic design procedures, all three products are treated equally.

Let us now assume that tests have confirmed that the insulator strength is distributed according to a normal distribution function with the following parameters:

Manufacturer A: average strength = 163 kN, standard deviation = 2 kN
Manufacturer B: average strength = 173 kN, standard deviation = 10 kN
Manufacturer C: average strength = 198 kN, standard deviation = 30 kN

A designer using deterministic design procedures will not be able to select the best product between these three manufacturers. If offered a choice, some designers will likely select the insulator having the highest average strength, i.e., manufacturer C.

The probability laws can confirm that the probability of not meeting the nominal strength of 160 kN is the same for all 3 manufacturers. This probability is 10%, based on a difference 1.28 σ between the average and the rated value. Consequently, all three products appear to be equivalent from a statistical point of view.

However, with further analysis, it can be demonstrated that the results will differ. In overhead lines, insulators are used in a string of many insulators and not as an individual component. Let us assume that our EHV line requires 20 insulators in a string and try to assess the strength data of strings of insulators that could be met with a 90% probability. Obviously, the strength of the string will be as low as that of the weakest insulator in the group of 20 composing this string.

Statistical laws provide us with the following strengths of the string (or a series of 20 insulators) corresponding to the probability of 10% of not being met[8]:

Manufacturer A: 157 kN
Manufacturer B: 147 kN
Manufacturer C: 123 kN

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[8] *Refer to Table A.5 of IEC 60826*

Consequently, it becomes obvious that the most reliable product to be used in a transmission line is from manufacturer A that has the least strength dispersion, despite the fact that its average strength is lower than the two others. Faced with many components that satisfy the product standard, designers should normally select the ones with the least dispersion or scatter in their strength. Reduction of the coefficient of variation (or scatter in strength) is obviously a sign of quality and is thus compensated in RBD methods because the latter allows designing the product much closer to the specified value. In practical terms, RBD can recognize the quality of a product and compensates its manufacturer.

3.5. Mismatch between suspension and angle tower strengths

Irrespective of the design approach (deterministic or RBD), it is commonly accepted that angle towers should be designed more reliable than tangent towers. In deterministic design approaches, this translates in using larger overload or safety factors for angle towers compared to tangent suspension towers. However, this treatment may not be sufficient to guarantee this objective, particularly when tangent towers are used at a fraction of their maximum spans.

The use factor of tangent towers (approximately equal to the ratio of actual span and the maximum span) can only be modeled and incorporated in the design process by means of statistical techniques such as detailed in IEC 60826. Failure to do so can result either in over designing the angle towers or facing their failure prior to tangent towers.

4. HOW RBD METHODS ADDRESS THE DEFICIENCIES OF DETERMINISTIC DESIGN PROCEDURES

The following basic principles are used by RBD methods in order to address the deficiencies stated above in deterministic methods:

4.1. Limit loads are specified

Contrary to deterministic methods that incorporate safety and/or overload factors, RBD specifies the limit loads[9] that the line has to withstand without damage. When limit loads are used, these are transferred to the conductors and then to hardware, to towers (suspension or dead-end) and to foundations. Therefore, each line component will be designed for the effects of the same limit loads considered for the line, without the risk of mismatch between components.

4.2. Loads and strength are recognized as random variables and treated as such

There is no disagreement between proponents of RBD or deterministic methods that loads (e.g. ice, wind, temperature and their combinations) and strengths are random variables. When the randomness of loads and strengths are taken into account, there is an immediate recognition that absolute reliability cannot be achieved and that there is always a risk that design loads can be exceeded or component’s strength can be less that design values.

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[9] *These loads are sometimes called ultimate loads, but the wording “limit” is a preferred one*

Therefore, RBD design standards will have to specify an acceptable maximum probability of failure (or its complement to one, the minimum reliability) and provide means to modulate these probabilities if warranted by economics or the importance of the project.

4.3. Design loads are selected based on the required return period

It is widely accepted that yearly maximum climatic loads such as ice and/or wind, follow extreme distribution functions. With such statistical functions, designers can associate a value of loads for any selected return period.

The return period is an important parameter for qualifying reliability. For example, if a 150 year return period load is selected as the limit load to design for, the probability of exceeding this load is $1/150 \approx 0.67\%$ per year. In a 50 year life span, the probability of exceeding the same load is $[1-(1-1/150)^{50}] \approx 28\%$.

4.4. The characteristic strength to be associated with load Q_T is also dependent on strength dispersion and is equal to 10% exclusion limit

Similarly, the strength is also a random variable, typically described by normal or log-normal distribution functions. The design strength is usually taken as the average minus 1 to 3 standard deviations. If the strength were chosen with an exclusion limit of 10%, this value would correspond to the average strength minus 1.28 x standard deviation in the case of a Normal distribution function.

4.5. The association of Q_T and (10%)R will yield an almost constant yearly reliability of the order of 1/(2T).

The line reliability and unreliability threshold corresponds to the condition where the load effect is equal to the strength. If load does not exceed strength, then the system (transmission line) is reliable. In the opposite case, the line would be in a failed condition.

If a load Q_T is associated with a strength corresponding to 10% exclusion limit, the resulting reliability is almost constant and equal to 1/(2T) in the normal range of variation of Q and R. This very significant relationship was uncovered and proven in previous papers and CIGRÉ reports written by the Author.

4.6. Yearly reliability can be customized by varying the return period T of design loads

Increasing reliability with RBD can be done very easily, either by selecting loads with a higher return period, or strength with a lower exclusion limit. The former approach is more practical and accurate and was selected by CIGRÉ and IEC.

5. HOW TO APPLY IEC 60826

5.1. Design steps of IEC 60826

The design methodology as per IEC60826 can be summarized in Figure 2 -. It is noted that activities (a) and (h) listed in this figure are not within the scope of IEC 60826.

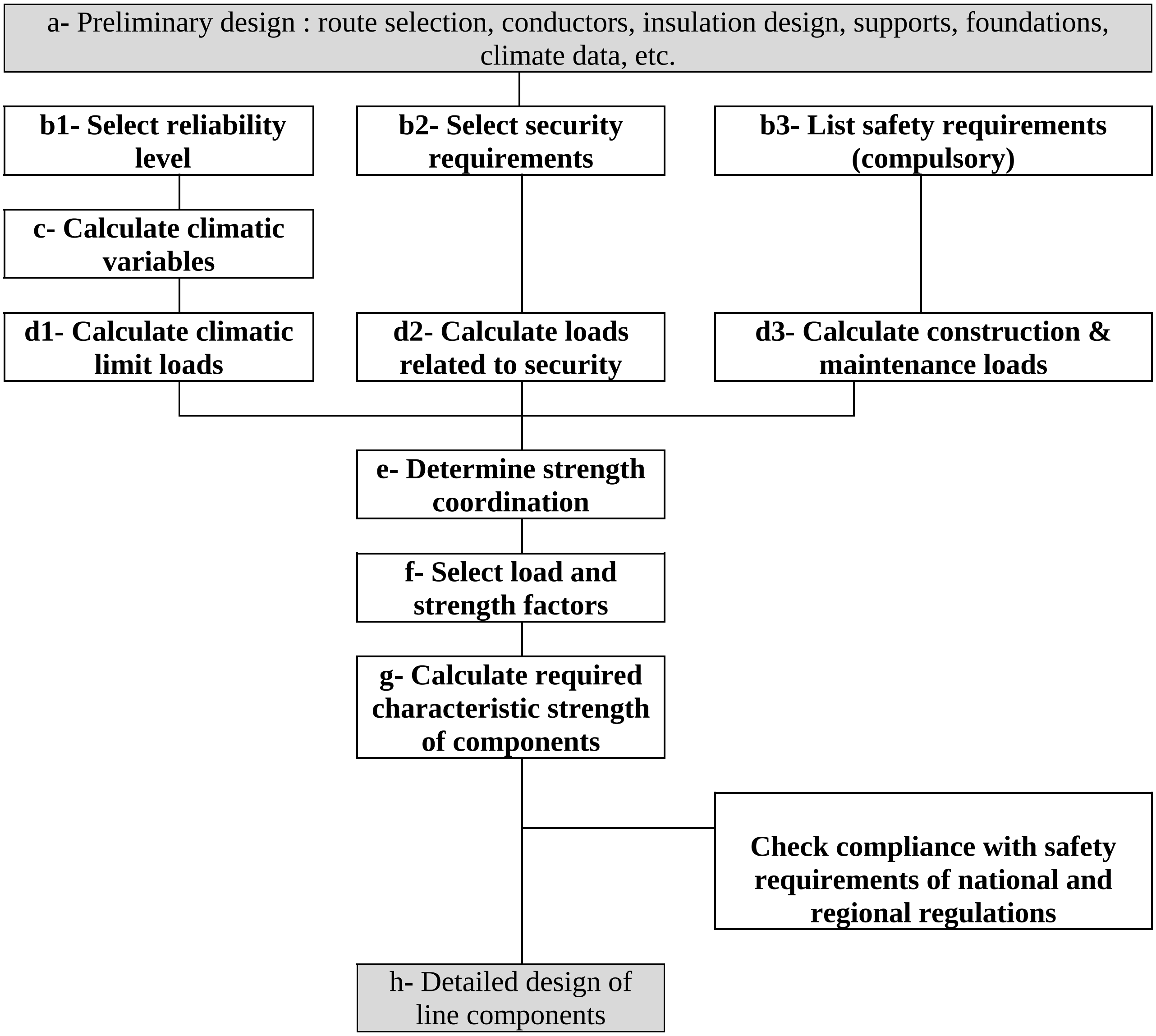

Figure 2 - Transmission line design methodology according to IEC 60826

5.2. Source of design requirements

The design according to IEC 60826 (see boxes b1, b2 and b3 in Figure 2 -) originates from the following requirements:

- Reliability: These requirements consist of climatic loads (wind, ice, temperature and their combinations) and aim to provide lines with satisfactory service performance. Statistical tools are used to quantify these loads.
- Security: These requirements aim to prevent or reduce risk of uncontrollable or cascading failures.
- Safety: These requirements aim to prevent human injury.

5.3. Reliability levels

Three reliability levels (I, II, III) are provided in IEC 60826. These levels correspond to return periods of design loads of 50, 150 and 500 years. In general,

- Level I is considered minimum for all permanent lines
- Level II applies to lines with voltages equal or exceeding 230 kV
- Level III applies to important lines in excess of 230 kV that are a unique source of supply.

Other levels can be selected based on local conditions or on an economical optimization between cost of increased reliability and present worth of future failures.

5.4. Security requirements

Security requirements relate to behavior of lines once failure is initiated. They aim to prevent uncontrolled propagation of failures (cascading). In such case, components are allowed to reach stresses very close to their ultimate limit state (failure). It is noted that in IEC 60826, security is a deterministic concept, while reliability is probabilistic.

Security and reliability requirements are interrelated because both tend to increase the required strength of components. Security measures, if more critical than climatic loads (reliability requirements), can also increase reliability.

5.5. Safety requirements

These are required to protect people from injury. They consist of construction and maintenance loads. It is aimed that the probability of failure under such loads should be very low.

5.6. Design equation, general format

$$\text{Load effect} < \text{Strength} \quad \text{or,}$$

$$Q_T < R_C \quad \text{or,}$$

$$\text{Load corresponding to a return period } T < \text{Characteristic strength } R_C$$

The above equation has been expanded in the IEC standard to the form below:

$$\gamma\, Q_T = \phi_R\, R_C$$

where,

γ factor for span dispersion, default value equal to 1.0 for new lines

Q_T load corresponding to a return period T

ϕ_R global strength factor equal to the product of $\phi_S * \phi_N * \phi_Q * \phi_C$
ϕ_S factor related to coordination of strength (sequence of failure)
ϕ_N factor related to number N of components
ϕ_Q factor related to the difference between tested and installed component
ϕ_C factor related to the statistical parameters of the characteristic strength

It is important to note that the load Q_T shall be the maximum along the space covered by the line. Furthermore, not only the maximum load intensity is important, but also its spatial coverage, as both affect design requirements and line reliability. Directional tendencies of wind or ice loads can be taken into account if confirmed; otherwise, it should be assumed that load direction always occurs in the most critical direction.

5.7. Loading cases and limit states

Limit states of strength of line components are defined for each component: a damage limit state (serviceability) and a failure (ultimate) limit state. Each group of loading requirements is associated with one of the limits states given below in Table 2.

Table 2 - Loading cases and limit states

Condition	Load case	Strength Limit State
Reliability	Climatic, ice, wind, wind + ice, with a return period T	Damage limit
Security	Failure limit (torsional and longitudinal)	Failure limit
Safety	Construction and maintenance loads	Damage limit

5.8. Differences between theoretical and actual reliabilities

IEC 60826 recognizes that the actual reliability may differ from the theoretical reliability when factors such the ones listed below are not properly accounted for:

- Actual use factors of components, particularly towers, are quite different from the assumed value of 1.0;
- The degree of correlation between loads and strengths;
- Direction of wind speed in relation to that of the line;
- Exclusion limit of strength different from the assumed 10%;
- Number of components subjected to maximum load intensity;
- Quality control during fabrication and construction.

Methods to take into account the above factors are covered in the subject standard.

5.9. Use factor of components

The use factor in IEC 60826 is defined as the ratio of the actual load (as built) to the limit design load of a component. For tangent towers, it is virtually equal to the ratio of actual to maximum design spans (wind or weight), and for angle towers, it also includes the ratio of the sines of the half angles of deviation (actual to design angles).

Use factor cannot exceed 1.0 and its influence on line reliability has been covered in the IEC standard. The use factor variation in overhead lines is inevitable because of the following reasons:

- Line components are mass fabricated;
- Components are not specifically designed for each tower location or use;
- Their design parameters reflect maximum usage along the line;
- Effective loads on line components are location dependent (span and tower height at each location).

Globally, the use factor variation increases reliability. However, a large dispersion of U may be an indication of a poor optimization (e.g. not enough tangent tower types or their parameters incorrectly selected). It is important to recognize that the preferred sequence of failure could also be altered if the use factor variation is not taken into account.

5.10. The characteristic strength R_C

IEC 60826 makes reference to the characteristic strength which is defined as the strength value guaranteed in relevant Standards. Sometimes, it is also called the guaranteed strength, the minimum strength, or the minimum failing load, and usually corresponds to an exclusion limit, from 2 to 5%, with 10% being an upper practical (and conservative) limit.

The strength distribution function is usually Normal (Gaussian). With stringent quality control, it tends to become a Log-normal function.

The characteristic strength can thus be calculated from the following equation, assuming it corresponds to a 10% exclusion limit:

$$R_C = (10\%)\ R = R\ (1 - k\ V_R)\text{, where:}$$

k = 1.28 for Normal distribution;
k = 1.08 to 1.26 for Log-normal distribution.

In case the maximum intensity of load is widespread and covers a large number (N) of structures, the strength distribution becomes that of chain or a series of N components whose strength is controlled by the weakest. Although the original distribution of strength can be Normal, that of the series of N structures will tend to be an Extreme (minima) type. Correction factors are provided in order to take into account the effect of the spatial coverage of the maximum load event on reliability (ϕ_N factor).

5.11. Strength coefficient ϕ_S related to sequence of failure

In IEC 60826, line components can be designed to fail (with a 90% probability) in a preferred mode called “preferred sequence of failure”. The best (or least damaging) failure mode is the one where the consequences of the first failure on the line are minimized. Strength factors allowing to target a preferred sequence of failure are provided in the standard. It is generally accepted that angle towers, dead-end towers, conductors or foundations should not fail first, thus leaving tangent towers as the one to fail first. The following table specifies the strength factors applicable to the strength of the component not to fail first.

Table 2 - Values of ϕ_S

		Coefficient of Variation (COV) of R_1			
		5%	7,5%	10%	20%
COV of R_2	0,05-0,10	0,92	0,87	0,82	0,63
	0,10-0,40	0,94	0,89	0,86	0,66

Note: in the above Table 2, R_2 is the component designed more reliable than R_1

5.12. Wind loads and limitations of wind calculations

Wind loads on conductors and tower structures are the source of important and critical loading requirement for overhead transmission lines. Methods to calculate wind forces, starting with a reference wind speed, are provided in the standard for the following conditions:

- Spans between 200 m and 800 m;
- Height of supports less than 60 m;
- Altitude below 1300 m.

5.13. Ground roughness

For the purpose of calculating wind pressure and forces, four (4) categories of ground roughness (also called terrain types) are provided:

- A- Flat coastal areas and deserts;
- B- Open country, cultivated fields;
- C- Numerous low height obstacles;
- D- Suburban areas.

5.14. Reference wind velocity

The reference wind velocity V_R considered in IEC 60826 consists of a 10 min. average, at 10 m height, in a terrain type B. The standard provides for conversion from other wind data, having different averages or located in a different terrain category, to the above reference value.

5.15. Wind speed design cases

High wind is combined with average minimum daily temperatures, and a reduced wind (60% of the reference value) is combined with the 50-year minimum temperature.

5.16. Wind load model

The conversion from wind speed to forces follows the equation:
Load = k ($\frac{1}{2}\ \tau\ \mu\ V^2$), where k is the product of:

- Height factor;
- Span factor;
- Response factor;
- Shape factor.

In IEC 60826, the k factor in the above equation takes the form of:

Wind force = $A\ C_x\ G_c\ G_L$ ($\frac{1}{2}\ \tau\ \mu\ V^2$), with:

G_c = Combined wind factor dependent on spans, height and terrain roughness category
G_L = Span factor
C_x = Drag (or force) coefficient
μ is the air mass per unit volume = 1.225 kg/m^3 (this is a default value, but adjustments of μ for different temperatures and altitudes are provided).
τ is the air density correction factor given in Table 5 of IEC 60826

A similar equation provides for calculation of wind forces applied to various types of transmission structures such as those made of angle sections, round pipe sections or steel poles. Drag coefficients are also provided for these tower types and take into account the compactness (or solidity ratio) of the windward face to reflect the shielding of wind on the leeward face.

5.17. Icing types

Ice accretion on conductors and structures are the source of important loads, and often control the design in many northern countries. The standard covers three types of ice accretion: precipitation icing, wet snow, and in-cloud icing. Methods to calculate design icing are provided and cover a range of cases with various availabilities of statistical data.

5.18. Ice loading cases

Once design ice thickness or weight of ice per unit length of conductors has been statistically defined, this value is used in the following loading cases:

- Uniform ice formation;
- Non uniform ice (longitudinal unbalanced icing, with all phases in a span subjected to the same unbalanced conditions);
- Torsional condition (unbalanced icing conditions occurring in opposite longitudinal directions thus creating a torsional moment on the structure).

5.19. Combined ice loads with wind

The presence of wind during or after icing episodes requires special loading cases and combinations of ice and wind loads in order to account for their combined effects.

The calculation of combined forces due to wind on ice covered conductors are provided in the standard and take into account: the ice thickness or ice weight per unit length of conductor, ice density, wind speed during icing, and drag coefficient of ice covered conductor.

Two combinations of ice, wind speed during icing, ice density/drag coefficient are provided for in the standard and consist of combining an extreme value of one variable (such as the 50 year value) with the average values of the other variables.

5.20. Construction and maintenance loads (safety requirements)

The loading conditions provided in the IEC standard supplement national regulations and safety codes. They are focused on reducing the risk of injuries to personnel working during construction and maintenance of the lines. These requirements should result in a very high reliability (risk of failure practically nil). The approach to deal with such loads is deterministic and consists of applying overload factors of 1.5 to 2.0 in order to insure such a high reliability. These loads are not usually combined with severe climatic loads, because construction and maintenance operations are not commonly undertaken during such weather events.

For example, loads during erection of supports are simulated by designing each support point for twice the static loads at sagging conditions. Under some conditions, and under controlled construction operations, the factor of 2.0 could be reduced to 1.5.

5.21. Security related loads

As explained earlier, these loads are intended to prevent cascading or uncontrollable failures. Minimum requirements are specified as follows:

- A broken phase load (torsional load) is applied on any one phase or ground wire attachment point, and is equivalent to the Residual Static load (RSL) calculated with bare conductors at average temperatures.
- A longitudinal load is specified, equivalent to a simulated fictitious ice load equal to the conductor weight applied on one side of the tower.

For lines that require a higher security level, additional security measures can be considered such as: Increasing the number of points where the RSL is applied, Considering the RSL in conjunction with some climatic load, and/or inserting anti-cascading towers.

5.22. Limit states of conductors and ground wires

An example of limit states of strength of conductors and ground wires is provided in Table 3.

Table 3 - Damage and failure limits of conductors and ground wires

Types	Damage limit	Failure limit
All types	Lowest of : - Vibration limit, or - The infringement of critical clearances defined by appropriate regulations, or - 75% of the characteristic strength or rated tensile strength (typical range in 70 % to 80 %)	Ultimate tensile stress (rupture)

5.23. Limit states of interface components

Typical strength limit states of interface components are provided in **Table 4**.

Table 4 - Damage and failure limit of interface components

Type of interface components	Damage limit[10]	Failure limit
Cable connectors: Dead-end and junction fittings and Suspension fittings	Unacceptable permanent deformation or slippage	Rupture
Insulators (porcelain and glass)	70 % strength rating or broken shed (glass only)	Rupture of pin, cap, cement or shed
Hardware	Critical[11] permanent deformation	Rupture of hardware or shear of bolts

6. CONCLUSION OF SECTION I

This paper summarizes advantages of RBD methods over common deterministic based methods as well as the key features of standard IEC 60826 and its companion document, CIGRÉ Technical Brochure 178.

Local weather conditions are taken into account during the design process, and tools are provided in order to increase reliability and security if warranted either by the importance of the line or by local conditions.

This RBD method of IEC 60826 Standard should provide for more economical design for a given target reliability compared to safety factor methods or, inversely, a higher reliability for given limit loads.

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[10] *Normally, hardware is designed in a manner to reduce or eliminate wear. Should wear be expected because of point to point contact, it should be considered in the design. In such case, the damage limit becomes: exceeding the excepted wear.*

[11] *Defined as the state where the hardware cannot be easily taken apart.*

The IEC 60826 has now been integrated in many international standards (ex. CSA C22.3, 2002, CENELEC EN 50341, IS 802, etc.) and utility practices. It represents a major contribution to the international trend in migrating toward reliability based design concepts in overhead line design.

7. REFERENCES

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CIGRE Technical Brochure

Reliability Based Design Methods for Overhead Lines Advantages, Applications and Comparisons

SECTION II - APPLICATIONS

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Working Group B2.06

April, 2006

SECTION II

APPLICATION OF IEC STANDARD 60826

Scope of Section II

The scope of Section II is to clarify the interpretations of IEC International Standard 60826 Ed. 3 (October 2003), recommend possible amendments and to provide an application example based on one given set of input parameters and compare the results with calculations based on the previous version i.e. IEC 826 TR, (1991) with the same input parameters.

PART A - EXPLANATIONS AND RECOMMENDATIONS TO IEC 60826

A.1 Introduction

In 1991 the International Electrotechnical Commission (IEC) published a Technical Report 826 entitled "Loading and Strength of Overhead Lines". This document introduced reliability and probabilistic concepts for calculation of loading and strength requirements for overhead lines components.

In 1996 CIGRÉ WG B2.06 published the Technical Brochure 109: “Review of IEC 82 - Loading and Strength of Overhead Lines". This Technical Brochure (TB) contains:

- A review of the use and application of IEC 826 TR based on a worldwide questionnaire,
- An application example with detailed description of premises, step-by-step calculations with references to the relevant clauses of IEC 826 TR and numerical results,
- An analysis of recent transmission line failures and
- A proposal of an improved rewritten standard for overhead line design: “Improved design criteria of overhead transmission lines based on reliability concepts”. The latter became to a large extent the basis for the main body of the international standard that was published in October 2003: IEC 60826 Ed. 3: ”Design criteria of overhead transmission lines”.

To justify the proposed improved standard in TB 109, CIGRÉ WG B2.06 published in 2001 the TB 178: “Probabilistic design of overhead lines” as a companion document to “Improved design criteria of overhead transmission lines based on reliability concepts” in TB 109. TB 178 contains the technical background of Reliability Based Design and the content of this Brochure is the main bases for the appendices incorporated in IEC 60826.

CIGRÉ, WG B2.06 was asked to provide a detailed calculation example to serve as a companion document for IEC 60826. During the preparation of this example, it was felt that possible inconsistencies or ambiguities of requirements, contradictions in IEC 60826, would be discovered. This should in turn lead to recommended changes to IEC 60826, issued by CIGRÉ to IEC/TC11.

In order to undertake this task, the same structure and set of input data for design of a typical line, that was used for the preparation of TB 109, is used to calculate load and strength requirements in accordance with the new International Standard IEC 60826 (2003), and compare the results with the calculations based on IEC 826 TR (1991). The computations of the loads according to IEC 60826, compared with IEC 826 TR are thoroughly discussed and assessed in Part C of this Section II. Specific recommendations are provided in order to propose clarifications and changes to some clauses of IEC 60826.

After approval, this document will be forwarded to IEC/TC11 for follow-up actions.

PART B - APPLICATION EXAMPLE OF IEC 60826

B.0 Foreword

In Technical Brochure 109 “Application of IEC Technical Report 826” wind and ice loadings are calculated according IEC Technical Report 826 (1991). In this Part B the same calculation example is used to calculate the wind and ice loads according to the new IEC International Standard 60826 Ed. 3.

B.1 Method

The example is divided in 3 Parts:

Part B - Apply the IEC 60826: ”Design criteria of overhead transmission lines” on the transmission line sections given on the enclosed profile with the technical and meteorological data specified below. Assess the available data.

Part C - Calculate ice, wind and combined wind and ice loads on conductors and earth wires, based on data available from another terrain category. For the case of ice loading, two calculations are performed as specified in B3.1 below.

Part D - Calculate the total loads on supports for the following towers by means of a line calculation program:

1:	tangent tower	BM 75	(suspension insulators)
2:	angle tower	BMV 73	(suspension insulators)
3:	tension tower	FMV 78	(strain insulators)

The towers are shown on an enclosed separate profile.

B.2 Technical information

- All towers are assumed rigid. Only insulator swing is used to balance asymmetrical loads.
- Only one value for the Modulus of Elasticity is used: E = 68 000 MPa for the conductor and E = 119 000 MPa for the earth wire.
- Creep of conductor and earth wire is not been taken into account in this study.
- Reliability level (Clause 2.1.2 in TR 826 (1991) and Clause 5.1.1.1 in IEC 60826 2003)) = 2.
- Terrain category (Clause 3.2.3.1 in TR 826 and Clause 6.2.2 in IEC 60826) = C (assumed for the general line topography).
- Information is found on the profile about:

Span lengths
Height differences
Tower angles

- Conductor and earth wire data:

	Conductor	Earth wire	Unit
Conductor type	Grackle	Goll	
Material	ACSR	AACSR	
Aluminium:	54 x 3,78	16 x 2,77	mm
Steel	19 x 2,27	19 x 2,40	mm
Overall diameter	34,03	17,54	mm
Overall cross section	682,88	182,37	mm^2
Nominal breaking strength	186,90	156,50	kN
Weight	2,28	0,945	kg/m
Modulus of elasticity	68 000	119 000	MPa
Coefficient of linear expansion	$19{,}4 \times 10^{-6}$	$14{,}20 \times 10^{-6}$	/°C
Every day stress (0°C)	60	105	N/mm^2
Every day tension	41,0	19,1	kN
Number of conductors per phase	1		
Weight insulator set	1500		kN
Length insulator set	4,0		m

- As the conductor height above ground (Z_c) is difficult to read from the profile, the following values are used (Note: These values represent average conductor heights for wind loading calculation):

70-71:	21 m	78-79:	14 m
71-72:	21 m	79-80:	28 m
72-73:	18 m	80-81:	16 m
73-74:	19 m	81-82:	17 m
74-75:	20 m	82-83:	16 m
75-76:	21 m	83-84:	17 m
76-77:	17 m		
77-78:	17 m		

Although section 2 of the profile (towers 78-84) is not included in the example (it is only asked for tensions in direction towards falling number on tower 78), the conductor heights of this section is given if a complete calculation of tower 78 is desirable for comparisons with own practices.

Height of the earth wire is 5 m above the conductor for all spans.

B.3 Meteorological information

B.3.1 Ice

Time series of ice loadings:
The following annual maxima of ice loadings have been recorded:

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

- Ice load from precipitation icing
- Type of ice: wet snow
- Temperature: 0 ºC

Two calculations are performed:

A: Calculation based on the full statistical information (Clause 3.3.1.2.2 in TR 826 and A 5.8.1 in IEC 60826)

B: Calculation based on the knowledge of the highest (overall) load in 12 years (34 N/m) (Clause 3.3.1.2.3 in TR 826 and A 5.8.1 in IEC 60826)

B.3.2 Wind

The time series of the maximum yearly 10 min wind speeds (perpendicular to the line) is measured 13 m above ground in terrain with terrain category B for the following 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
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		

These wind data available for terrain category B have to be converted to terrain category C assumed for the line section considered.

Coincident temperature = 0°C (Clause 3.2.4.1.4 in 826 and 6.4.3 in IEC 60826)

Reduced wind speed:

- Min. temperature = -18°C (Clause 3.2.4.2.1 in 826 and 6.2.4 in IEC 60826)
- Reduced wind speed = 0.6 Vr (Clause 3.2.4.2.2 in 826 and 6.2.4 in IEC 60826)

B.3.3 Combined wind and ice

Wind reduction factor B_i:

In IEC 60826, the suggested range for B_i is: 0,6 – 0,85.
The chosen value is: $B_i = 0,75$ (Clause 3.4.2.2.1.4 in 826 and 6.4.4.1 in IEC 60826)

Wind speed coefficient of variation (COV):

$\sigma_{Vem}/\overline{V}em = \sigma_{Vm}/\overline{V}_m = 0,18$ (Clause 3.4.2.2.1.4 in 826 and A 4.5.2 in IEC 60826)

Ice load coefficient of variation (COV):

$\sigma_g/\overline{g} = 0,70$ (is used)
$\sigma_g/\overline{g} = 0,82$ (is calculated) (Clause 3.4.2.1 in 826 and A 5.8.1 in IEC 60826)

Number of years = 12.

PART C - A STEP BY STEP CALCULATION OF THE APPLICATION EXAMPLE

C.0 Introduction

The following calculations based on revised IEC 60826 "Probabilistic design of overhead lines" (October 2003) are compared with the calculations presented in CIGRÉ Technical Brochure 109 "Loading and strength of overhead lines".

Some comments are given at the end of each clause.

The calculated loads on conductors and earth wires are summarized in tables 1A, 1B, 2A and 2B. The results of the calculations of the total loads on supports are presented in tables 3A and 3B.

Comments to the 2003 edition of IEC 60826

The factors $K_{\sigma g}$ and K_n and the formula for reference ice load, g_R, are not found in IEC 60826 Ed. 3, see section 6.3.4. The formula for g_R is given in equation 6.3 in CIGRÉ TB 178 i.e. $g_R = K_{\sigma g} K_n K_d K_h \bar{g}$ where $\bar{g}$ is the mean value. In IEC 60826 Ed. 3 clause 6.2.3 “Reference wind load V_R” and clause 6.3.4 “Reference limit ice load” it is said that the reference load for wind, $V_{R,}$ and for ice, g_R, can be determined by statistical analysis of relevant wind and ice data.

Here references to the direct calculation of these design loads using the Gumbel distribution in clause B.2.1 equation B.7 and clause C.4.2 using equations C.27, C.28 and C.29 are missed.

In section A4.5.2 “Reference wind speed for design” the second paragraph starts: ”The reference V_R is determined from…….” This sentence is difficult to understand and should be replaced by:

“For finite number of observations, the reference wind speed V_R with a given return period T is determined from the mean value, standard deviation and parameters C_1 and C_2 using equation B.7. The parameters C_1 and C_2 are calculated by using equations C.27, C.28 and C.29. For infinite observations equation B.8 or table C.1 should be used.”

In clause 6.3.2 and 6.4.6.2 there is a misprint: The number 9,82 should be 9,81

Factors that are equal for several load cases

$\sin^2\Omega$ = 1,00
diameter conductor = 34,03 mm
diameter earth wire = 17,54 mm

C.1 Wind Load

Given parameters

Terrain category of line = C
Reliability level = 2
N = 29 years

The wind speeds are measured in terrain with terrain category B and 13 m above ground.

$V_{10} = V_{13}/(13/10)^{0,16}$ (eq. A.36)
$\overline{V}_m = \sum (v_{10} / 29)$ = 15,42 m/s
σ_{Vm} = 2,72 m/s

In CIGRE Technical Brochure 109 values for the Gumbel constants C1 and C2 corresponding with infinite observations are used. For the purpose of the comparison the same premises are used. Normally it is recommended to use the correct number of observations to calculate the reference load.

C1 (infinite observations) = 1,28255 (Table C.1)
C2 (infinite observations) = 0,57722 (Table C.1)
V_R = 24,83m/s (eq. B7)
τ = 1,00 (table 5)
μ = 1,225 kg/m^3 (clause 6.2.5)
K_R = 0,85 (table 4)
$q_0 = 0,5\tau\mu K_R^2 V_R^2$ = 272,7 N/m^2 (eq. 7)
C_{xc} = 1,00 (clause 6.2.6.1)
$A_c = q_0 C_{xC} G_c G_L \sin^2\Omega dL$ (eq. 8)

Reduced Wind

Min. temperature = -18,00 ^{o}C
$V_R red. = 0,6V_R$ = 14,90 m/s (clause 6.2.4)
$q_0 = 0,5\tau\mu K_R^2 V_R red^2$ = 98,20 N/m^2
$A_c red = q_0 C_{xC} G_c G_L \sin^2\Omega dL$

Comparison of the CIGRÉ TB 109 calculation with IEC 826 (1991)

- $K_R V_R$ is now $0,85 \cdot 24,83 = 21,11$ compared with 21,37 according IEC 826 (1991).
- The span factor, G_L, was not included in IEC 826 (1991), but integrated in the combined wind factor G_c.
- The values found for the combined wind factor, G_c, are now higher compared with IEC 826 (1991).
- The resulting values of the wind load on conductors, A_C, are about 1% to 5% higher compared with IEC 826 (1991).

C.2A Ice without Wind (based on full statistical information)

Number of years with observation, N = 12.

$\bar{g}$ = 12,92 N/m

σ_g = 10,65

$\sigma_g / \bar{g}$ = 0,82 (note: 0,70 is used)

C1 = 0,98327 (eq. C.29

C2 = 0,50350 (eq. C.28)

$K_{\sigma g}K_n$ = 4,21 (3,42·1,23) (not found in standard, but taken from TB 178)

$K_d$conductor = 1,05 (eq. A53, precipitation icing)

$K_d$earthwire = 0,85 (eq. A3, precipitation icing)

$g_R = K_{\sigma g} \cdot K_n \cdot K_d \cdot K_h \cdot \bar{g}$ (not found in standard, but taken from TB 178)

(g_R could have been calculated by using equations C.27, C.28 C.29 and B.7 in IEC 60826 Ed. 3)

Comparison of the CIGRÉ TB 109 calculation with IEC 826 (1991)

- K_d for conductor and earth wire are lower (1,05 and 0,85 versus 1,06 and 0,90)
- K_h for precipitation icing varies for each span depending on height above ground, compared with the value 1,00 for all spans in the calculation using figure 15 in IEC 826 (1991). This change is described in clause 6.3.4.1 in IEC 60826. The clause deals with reference limit ice load based on statistical data. Clause 6.3.4.1 reads:

"*The reference design load g_R, or t_R if ice thickness is chosen as the ice variable, are the reference limit ice loads corresponding to the selected return period T (function of the reliability level of the line). The g_R or t_R values can be directly obtained from the statistical analysis of data obtained either from direct measurements, icing models, or appropriate combinations of both.*

NOTE 1: The figures and equations given in this subclause are based on g_R (N/m) being the ice variable. However, equation (13) can be used to convert from g_R to t_R if the latter is chosen as the ice variable.

If data is measured (or model simulated) on conductor diameters and heights typical of the line, there will not be any further adjustment to this value. However, if data is measured at the assumed reference height of 10 m on a 30 mm conductor diameter, g_R should be adjusted by multiplying it with a diameter factor K_d and a height factor K_h applicable to the actual line conditions.

K_d is given in Figure 10.

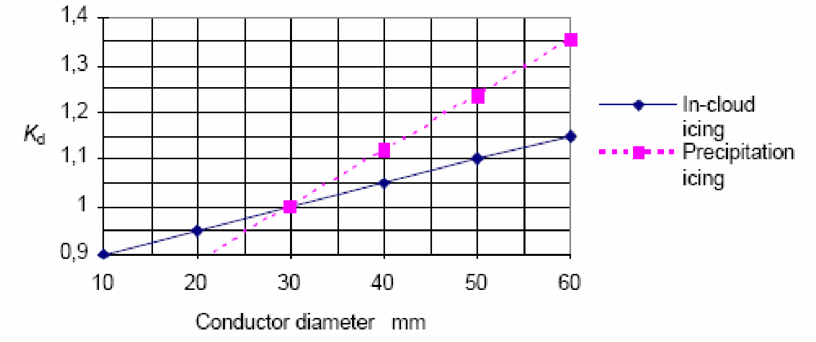


Figure 10 – Factor K_d related to the conductor diameter

For both types of icing, when $K_d \cdot \bar{g}$ exceeds 100 N/m, the value of K_d is no longer increased.
If $\bar{g}$ (average of yearly maximum values of g) is above 100 N/m and d greater than 30 mm, K_d is considered equal 1,0.

K_d describes the variation of g with the height of conductors above the ground. Its value is given in Figure 11.

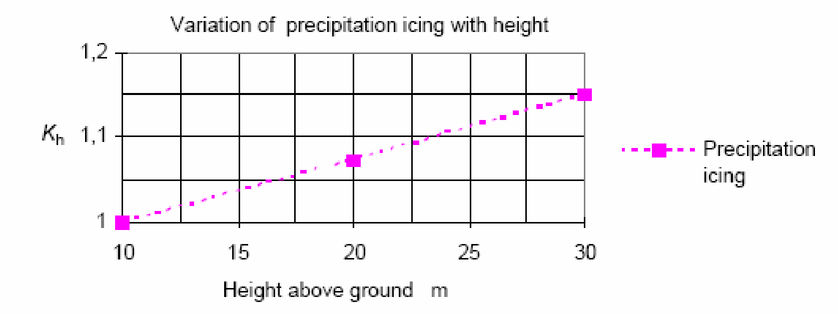


Figure 11 – Factor K_h related to the conductor height

As a simplification, it is suggested that the value g_R be the same for phase conductors and ground wires in the same span, but there is growing evidence that the higher ground wire may accumulate more ice for some types of ice accretion. For variation of in-cloud icing accretion with height, refer to comments in A.5.8.2.”

In this case data is measured at the assumed reference height of 10 m on a 30 mm conductor diameter. Therefore the values used for K_h are specified for each span in the tables 1A, 2A, 1B and 2B and they are in the range of 5% to 12 % larger than K_h = 1,0 as used in IEC 826 (1991).

The resulting reference ice load g_R is about 3% to 7% higher and varies for each span compared with one value equal 1.0 for all spans in the first calculation using IEC 826 (1991).

C.2B Ice without Wind (based on maximum ice load)

g max = 34,00 N/m
$\bar{g} = 0{,}45\, g$ max = 15,30 N/m
$\sigma_g / \bar{g}$ = 0,50
C1 = 0,98327
C2 = 0,50350
$K_{\sigma g}K_n$ = 3,29 (not found in standard, but taken from TB 178)
$g_R = K_{\sigma g} \cdot K_n \cdot K_d \cdot K_h \cdot \bar{g}$ (not found in standard, but taken from TB 178)
(g_R could have been calculated by using equations C.27, C.28 C.29 and B.7 in IEC 60826 Ed. 3)

C.3A Combined Wind and Ice Loading (based on full statistical information)

$C_{iH} = 1,0$ (table A14)
$\delta = 600,0\ \mathrm{kg/m^3}$ (table A14)
$\pi = 3,142$

Condition 1 (Low probability ice load with moderate wind)

$g_L = g_R$ (6.4.2)
$B_i = 0,45$ (chosen value, 6.4.4.1)
$V_{iH} = B_i V_R = 11,2\ \mathrm{m/s}$ (6.4.4.1)
$q_{0H} = 0,5\mu\tau K_R^2 V_{iH}^2 = 55,2\ \mathrm{N/m^2}$ (6.4.6.1)
$D_L = (d^2+4g_L/(9,81\pi\delta))^{0,5}$ (6.4.6.2)
$A_{c1} = q_{0H} C_{iH} G_c G_L D_L L \sin^2\Omega$ (6.4.6.2)

Condition 2 (Low probability wind load with moderate ice)

$g_H = 0,4g_R$ (6.4.2)
$B_i = 0,75$ (chosen value, 6.4.4.1)
$V_{iL} = B_i V_R = 18,6\ \mathrm{m/s}$ (6.4.4.1)
$q_{0L} = 0,5\mu\tau K_R^2 V_{iL}^2 = 153,4\ \mathrm{N/m^2}$ (6.4.6.1)
$D_H = (d^2+4g_H/(9,81\pi\delta))^{0,5}$ (6.4.6.2)
$A_{c2} = q_{0L} C_{iH} G_c G_L D_H L \sin^2\Omega$ (6.4.6.2)

Comparison of the CIGRÉ TB 109 calculation with IEC 826 (1991)

- The high probability ice load in combined events, $g_H = 0,4g_R$ is used in IEC 60826 instead of the factors $K_{\sigma L}$ and $K_{\sigma H}$ from table 17 in IEC 826 (1991)
- Values for B_i for condition 1 and 2 differ compared with IEC 826 (1991)
- The factors $K_{iH,}$ K_{iL} and K_n in IEC 826 (1991) are not longer included
- The factor G_L was not included as a separate variable in IEC 826 (1991) but integrated in the combined G_c

For the result of calculations based on full statistical information, see Tables 1A, 2A and 3A:

Table 1A - Calculated loads on conductor based on full statistical information
Table 2A - Calculated loads on earth wire based on full statistical information
Table 3A - Calculated loads on supports based on full statistical information

C.3B Combined Wind and Ice Loading (based on maximum ice load)

Formulas: see C.3A
For the result of calculations based on maximum ice load, see Tables 1B, 2B and 3B:

Table 1B - Calculated loads on conductor based on maximum ice load
Table 2B - Calculated loads on earth wire based on maximum ice load
Table 3B - Calculated loads on supports based on maximum ice load

PART D - CONCLUSION OF SECTION II

The following conclusions can be drawn from the following tables:

Table 4A - Comparison of conductor and earth wire forces according to the 1991 and the 2003 edition based on full statistical information

Table 4B - Comparison of conductor and earth wire forces according to the 1991 and the 2003 edition based on maximum ice load

In the Tables 4A and 4B, 1991 edition (a) and 2003 edition (b) are compared. The relative difference $100^{\cdot}(F_b\text{-}F_a)/F_a$ is given. Figures in brackets are absolute values in kN.

Transversal forces for combined load conditions wind and ice and longitudinal forces for load condition non-uniform ice are higher, most of the other forces are lower.

The differences in forces due to high and low wind are small i.e. in the range of 0% to 3%. Insignificant larger % values occur when the compared absolute values are small. Thus the calculations of wind loads according IEC 60826 (2003) are consistent with calculations according IEC Technical Report 826 (1991) with insignificant load differences on conductors and towers.

The largest differences occur for ice loads mainly due to the fact that ice accretions increases with the height for precipitation ice as described in clause C.2A. In this case the highest differences are in the range of 25% to 31%. The calculations reveal that the improved description of ice loads in IEC 60826 is important and that proper quality ice measurements combined with development of ice models are important in countries exposed to atmospheric icing.

TABLE 1A - Calculated loads on conductor based on full statistical information

			SPAN								
			70-71	**71-72**	**72-73**	**73-74**	**74-75**	**75-76**	**76-77**	**77-78**	
	Height above ground	Zc	21	21	18	19	20	21	17	17	m
	Span length	L	297	317	332	282	504	362	412	314	m
	Combined wind factor	G_c	2,40	2,40	2,33	2,36	2,39	2,40	2,30	2,30	
	Span factor	G_L	0,970	0,967	0,964	0,979	0,914	0,955	0,940	0,967	
	Factor related to the conductor height	K_h	1,083	1,083	1,060	1,068	1,075	1,083	1,053	1,053	
WIND LOAD											
High wind speed	Dynamic reference pressure	q_0	273								N/m^2
	Wind load	A_c	6,4	6,8	6,9	6,0	10,2	7,7	8,3	6,5	kN
Reduced wind speed	Dynamic reference pressure	q_0	98								N/m^2
	Wind load	A_c	2,3	2,5	2,5	2,2	3,7	2,8	3,0	2,3	kN
ICE WITHOUT WIND											
Condition 1. Uniform ice	Ice load	gR	62	62	60	61	61	62	60	60	N/m
Condition 2. Non-uniform ice	Max. ice load	$0,7*g_R$	43	43	42	43	43	43	42	42	N/m
	Min. ice load	$0,4*0,7*g_R$	17	17	17	17	17	17	17	17	N/m
COMBINED WIND AND ICE											
Condition 1. Uniform ice	Ice load	g_L	62	62	60	61	61	62	60	60	N/m
	Dnamic reference pressure	q_{0H}	55								N/m^2
	Wind load	A_{c1}	4,6	4,9	4,9	4,3	7,3	5,5	5,8	4,6	kN
	Equivalent diameter of ice	D_L	120	120	119	120	120	120	119	119	mm
Condition 2. Non-uniform ice	Ice load	g_H	25	25	24	24	24	25	24	24	N/m
	Dynamic reference pressure	q_{0L}	153								N/m^2
	Wind load	A_{c2}	8,5	9,1	9,1	8,0	13,6	10,3	10,9	8,5	kN
	Equivalent diameter of ice	D_H	81	81	80	80	80	81	80	80	mm

TABLE 1B - Calculated loads on conductor based on max. ice load

			SPAN								
			70-71	**71-72**	**72-73**	**73-74**	**74-75**	**75-76**	**76-77**	**77-78**	
	Height above ground	Zc	21	21	18	19	20	21	17	17	m
	Span length	L	297	317	332	282	504	362	412	314	m
	Combined wind factor	G_c	2,40	2,40	2,33	2,36	2,39	2,40	2,30	2,30	
	Span factor	G_L	0,970	0,967	0,964	0,979	0,914	0,955	0,940	0,967	
	Factor related to the conductor height	K_h	1,083	1,083	1,060	1,068	1,075	1,083	1,053	1,053	
ICE WITHOUT WIND											
Condition 1. Uniform ice	Ice load	gR	57	57	56	56	57	57	55	55	N/m
Condition 2. Non-uniform ice	Max. ice load	$0,7*g_R$	40	40	39	39	40	40	39	39	N/m
	Min. ice load	$0,4*0,7*g_R$	16	16	16	16	16	16	16	16	N/m
COMBINED WIND AND ICE											
Condition 1. Uniform ice	Ice load	g_L	57	57	56	56	57	57	55	55	N/m
	Dynamic reference pressure	q_{0H}	55								N/m^2
	Wind load	A_{c1}	4,4	4,7	4,7	4,2	7,0	5,3	5,5	4,4	kN
	Equivalent diameter of ice	D_L	116	116	115	115	116	116	115	115	mm
Condition 2. Non-uniform ice	Ice load	g_H	23	23	22	23	23	23	22	22	N/m
	Dynamic reference pressure	q_{0L}	153								N/m^2
	Wind load	A_{c2}	8,3	8,8	8,9	7,8	13,1	9,9	10,5	8,3	kN
	Equivalent diameter of ice	D_H	78	78	77	78	78	78	77	77	mm

TABLE 2A - Calculated loads on earth wire based on full statistical information

			SPAN								
			70-71	**71-72**	**72-73**	**73-74**	**74-75**	**75-76**	**76-77**	**77-78**	
	Height above ground	Zc	26	26	23	24	25	26	22	22	m
	Span length	L	297	317	332	282	504	362	412	314	m
	Combined wind factor	G_c	2,51	2,51	2,45	2,47	2,49	2,51	2,43	2,43	
	Span factor	G_L	0,970	0,967	0,964	0,979	0,914	0,955	0,940	0,967	
	Factor related to the conductor height	K_h	1,120	1,120	1,098	1,105	1,113	1,120	1,090	1,090	
WIND LOAD											
High wind speed	Dynamic reference pressure	q_0	273								N/m^2
	Wind load	A_c	3,5	3,7	3,8	3,3	5,5	4,2	4,5	3,5	kN
Reduced wind speed	Dynamic reference pressure	q_0	98								N/m^2
	Wind load	A_c	1,2	1,3	1,4	1,2	2,0	1,5	1,6	1,3	kN
ICE WITHOUT WIND											
Condition 1. Uniform ice	Ice load	gR	52	52	51	51	52	52	51	51	N/m
Condition 2. Non-uniform ice	Max. ice load	$0{,}7*g_R$	36	36	36	36	36	36	35	35	N/m
	Min. ice load	$0{,}4*0{,}7*g_R$	15	15	14	14	14	15	14	14	N/m
COMBINED WIND AND ICE											
Condition 1. Uniform ice	Ice load	g_L	52	52	51	51	52	52	51	51	N/m
	Dynamic reference pressure	q_{0H}	55								N/m^2
	Wind load	A_{c1}	4,3	4,6	4,6	4,0	6,8	5,2	5,5	4,3	kN
	Equivalent diameter of ice	D_L	108	108	106	107	107	108	106	106	mm
Condition 2. Non-uniform ice	Ice load	g_H	21	21	20	21	21	21	20	20	N/m
	Dynamic reference pressure	q_{0L}	153								N/m^2
	Wind load	A_{c2}	7,7	8,2	8,3	7,2	12,2	9,2	9,9	7,7	kN
	Equivalent diameter of ice	D_H	69	69	69	69	69	69	68	68	mm

TABLE 2B - Calculated loads on earth wire based on max. ice load

			SPAN								
			70-71	**71-72**	**72-73**	**73-74**	**74-75**	**75-76**	**76-77**	**77-78**	
	Height above ground	Zc	26	26	23	24	25	26	22	22	m
	Span length	L	297	317	332	282	504	362	412	314	m
	Combined wind factor	G_c	2,51	2,51	2,45	2,47	2,49	2,51	2,43	2,43	
	Span factor	G_L	0,970	0,967	0,964	0,979	0,914	0,955	0,940	0,967	
	Factor related to the conductor height	K_h	1,120	1,120	1,098	1,105	1,113	1,120	1,090	1,090	
ICE WITHOUT WIND											
Condition 1. Uniform ice	Ice load	gR	48	48	47	48	48	48	47	47	N/m
Condition 2. Non-uniform ice	Max. ice load	$0{,}7*g_R$	34	34	33	33	34	34	33	33	N/m
	Min. ice load	$0{,}4*0{,}7*g_R$	13	13	13	13	13	13	13	13	N/m
COMBINED WIND AND ICE											
Condition 1. Uniform ice	ce load	g_L	48	48	47	48	48	48	47	47	N/m
	Dynamic reference pressure	q_{0H}	55								N/m^2
	Wind load	A_{c1}	4,1	4,4	4,4	3,9	6,5	5,0	5,3	4,2	kN
	Equivalent diameter of ice	D_L	104	104	103	103	103	104	102	102	mm
Condition 2. Non-uniform ice	Ice load	g_H	19	19	19	19	19	19	19	19	N/m
	Dynamic reference pressure	q_{0L}	153								N/m^2
	Wind load	A_{c2}	7,4	7,9	8,0	7,0	11,7	8,9	9,5	7,5	kN
	Equivalent diameter of ice	D_H	67	67	66	66	67	67	66	66	mm

TABLE 3A - Calculated loads on supports (kN) based on full statistical information

TOWER NO. BM 75

	Conductor			Earth wire		
	Longitudinal	Vertical	Transversal	Longitudinal	Vertical	Transversal
High wind speed	0,0	-8,9	9,0	-0,5	-2,7	4,8
Low wind speed	0,0	-9,1	3,2	0,6	-3,0	1,7
Uniform ice	-0,9	-32,5	0,0	-11,0	-22,8	0,0
Non-uniform ice	-3,9	-22,5	0,0	-23,1	-14,4	0,0
Wind and ice, condition 1	-0,9	-32,4	6,4	-11,2	-22,8	5,9
Wind and ice, condition 2	-0,3	-18,0	11,9	-5,8	-10,3	10,6

TOWER NO. BMV 73

	Conductor			Earth wire		
	Longitudinal	Vertical	Transversal	Longitudinal	Vertical	Transversal
High wind speed	0,1	-13,3	26,1	-0,5	-5,4	13,3
Low wind speed	-0,2	-12,8	19,8	-0,3	-5	9,7
Uniform ice	1,9	-37,3	41,2	-5	-24,7	25,2
Non-uniform ice	3,7	-26,2	30,9	-16,3	-15,8	18,4
Wind and ice, condition 1	1,9	-37,4	46,2	-5,1	-24,8	30,0
Wind and ice, condition 2	0,8	-23,4	38,6	-3,0	-13,7	26,5

TOWER NO. FMV 78 (towards tower 77)

	Conductor			Earth wire		
	Longitudinal	Vertical	Transversal	Longitudinal	Vertical	Transversal
High wind	-48,8	-6,1	21,2	-24,4	-2	10,7
Low wind	-43,4	-6	17,1	-20,8	-1,9	8,3
Uniform ice	-103,7	-16,6	38,1	-63,8	-10,8	23,4
Non-uniform ice	-81,2	-10,5	29,8	-52,4	-8,2	19,2
Wind and ice, condition 1	-104,9	-16,7	40,8	-64,9	-10,8	26,0
Wind and ice, condition 2	-75,5	-10,4	32,0	-47,1	-5,7	21,2

TABLE 3B - Calculated loads on supports (kN) based on max. ice load

TOWER NO. BM 75

	Conductor			Earth wire		
	Longitudinal	Vertical	Transversal	Longitudinal	Vertical	Transversal
Uniform ice	-1	-30,8	0	-10,3	-21,3	0
Non-uniform ice	-3,7	-21,6	0	-21,6	-13,5	0
Wind and ice, condition 1	-1	-30,7	6,2	-10,4	-21,2	5,7
Wind and ice, condition 2	-0,4	-17,4	11,5	-5,4	-9,7	10,3

TOWER NO. BMV 73

	Conductor			Earth wire		
	Longitudinal	Vertical	Transversal	Longitudinal	Vertical	Transversal
Uniform ice	1,7	-35,5	39,6	-4	-23,4	24,2
Non-uniform ice	3,4	-25,2	29,9	-14,9	-15,1	17,7
Wind and ice, condition 1	1,7	-35,6	444,4	-4,1	-23,5	28,8
Wind and ice, condition 2	0,7	-22,6	37,6	-2,4	-13,2	25,7

TOWER NO. FMV 78 (towards tower 77)

	Conductor			Earth wire		
	Longitudinal	Vertical	Transversal	Longitudinal	Vertical	Transversal
Uniform ice	-99,4	-15,8	36,5	-60,9	-10,1	22,4
Non-uniform ice	-78,2	-10,1	28,7	-50,2	-7,7	18,4
Wind and ice, condition 1	-100,5	-15,8	39,1	-62,0	-10,2	24,8
Wind and ice, condition 2	-73,3	-10,0	31,0	-45,6	-5,4	20,5

Table 4A - Comparison of conductor and earth wire forces according to the 1991 and the 2003 edition based on full statistical information

a = 1991 edition
b = 2003 edition

Comparison of relative difference = $100 \cdot (F_b - F_a)/F_a$. Figures in brackets are absolute values in kN.

	Conductor			Earth wire		
	Long.	Vert.	Trans.	Long.	Vert.	Trans.
Tower BM 75						
High wind speed	0	1 (0,2)	-1 (0,1)	0	0	-2 (0,1)
Low wind speed	0	2 (0,2)	-3 (0,1)	0	3 (0,1)	-6 (0,1)
Uniform ice	13 (0,1)	5 (1,6)	0	6 (0,6)	6 (1,2)	0
Non-uniform ice	-22 (1,1)	10 (2,0)	0	-18 (5,2)	13 (1,6)	0
Wind and ice, condition 1	13 (0,1)	5 (1,6)	-31 (2,9)	6 (0,6)	7 (1,5)	-31 (2,7)
Wind and ice, condition 2	50 (0,3)	13 (2,1)	-16 (2,3)	7 (0,4)	20 (1,7)	-16 (2,0)
Tower BMV 73						
High wind speed	-	2 (0,2)	0 (0,1)	0	2 (0,1)	-1 (0,1)
Low wind speed	0	2 (0,3)	1 (0,2)	-25 (0,1)	2 (0,1)	2 (0,2)
Uniform ice	6 (0,1)	4 (1,4)	4 (1,5)	4 (0,2)	4 (0,9)	3 (0,7)
Non-uniform ice	-18 (8,2)	10 (2,3)	15 (4,0)	-23 (4,8)	12 (1,7)	10 (1,6)
Wind and ice, condition 1	6 (0,1)	3 (1,2)	-3 (1,3)	2 (0,1)	4 (0,9)	-5 (1,7)
Wind and ice, condition 2	14 (0,1)	7 (1,6)	-4 (1,5)	7 (0,2)	9 (1,1)	-6 (1,8)
Tower FMV 78						
High wind speed	1 (0,3)	2 (0,1)	0	0	5 (0,5)	-1 (0,1)
Low wind speed	2 (0,7)	3 (0,2)	1 (0,2)	1 (0,3)	6 (0,1)	1 (0,1)
Uniform ice	3 (3,3)	3 (0,5)	3 (1,2)	3 (1,9)	5 (0,5)	3 (0,7)
Non-uniform ice	6 (4,4)	15(1,4)	6 (1,6)	3 (1,5)	5 (0,4)	3 (0,5)
Wind and ice, condition 1	2 (1,9)	3 (0,5)	-1 (0,4)	1 (0,9)	5 (0,5)	-3 (0,7)
Wind and ice, condition 2	2 (1,2)	8 (0,8)	-2 (0,5)	-1 (0,5)	14 (0,7)	-4 (0,9)

Table 4B - Comparison of conductor and earth wire forces according to the 1991 and the 2003 edition based on max ice load

a = 1991 edition
b = 2003 edition

Comparison of relative difference = $100 \cdot (F_b - F_a)/F_a$. Figures in brackets are absolute values in kN.

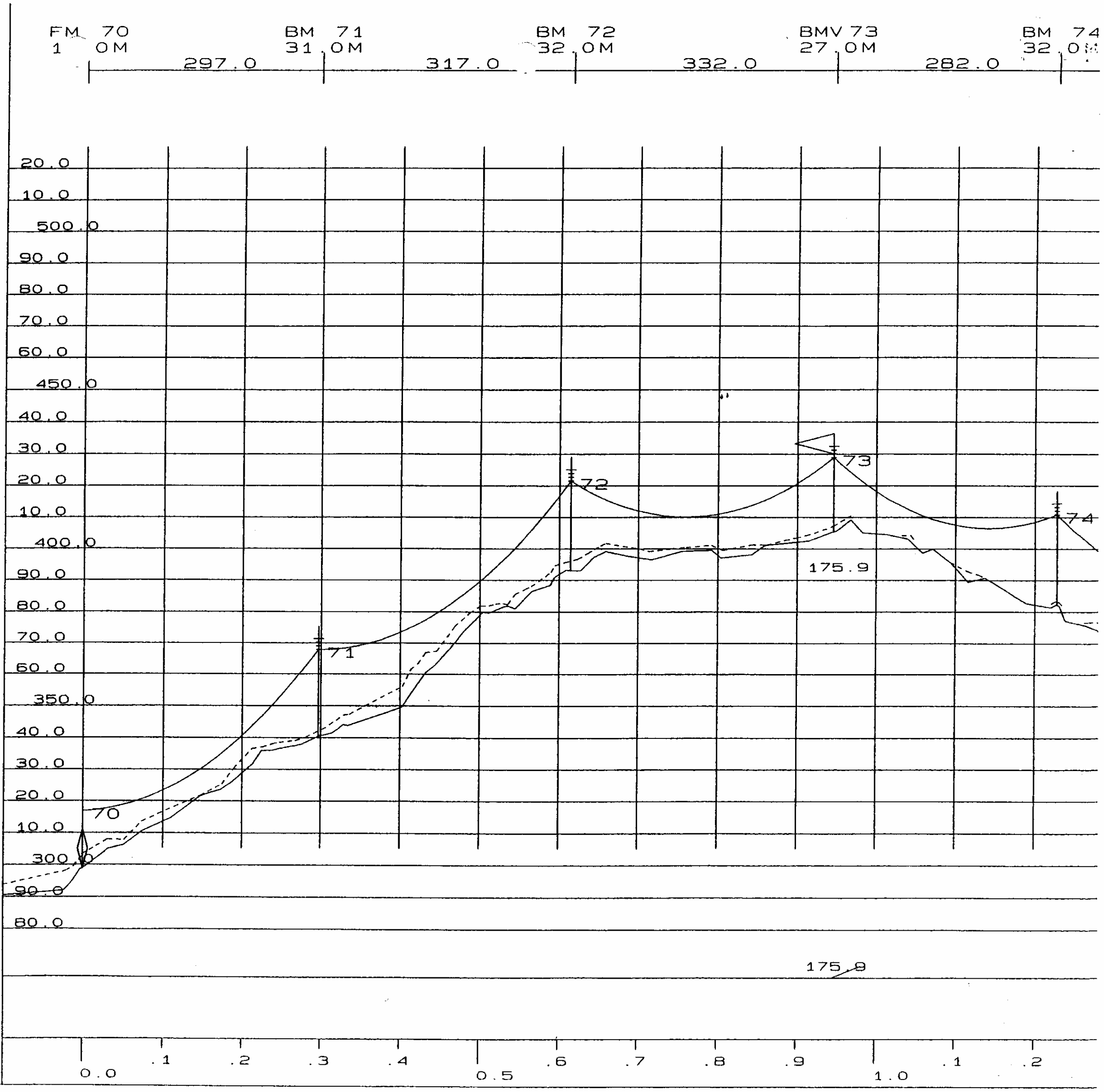
	Conductor			Earth wire		
	Long.	Vert.	Trans.	Long.	Vert.	Trans.
Tower BM 75						
Uniform ice	43 (0,3)	5 (1,4)	0	5 (0,5)	6 (1,2)	0
Non-uniform ice	-20 (0,9)	9 (1,8)	0	-18 (4,9)	13 (1,5)	0
Wind and ice, condition 1	43 (0,3)	5 (1,5)	-31 (2,8)	2 (0,2)	5 (1,0)	-31 (2,6)
Wind and ice, condition 2	33 (0,1)	5 (0,8)	-22 (3,3)	-8 (0,5)	5 (0,5)	-22 (2,9)
Tower BMV 73						
Uniform ice	6 (0,1)	3 (1,1)	3 (1,3)	-13 (0,6)	4 (1,0)	4 (0,9)
Non-uniform ice	-17 (7,5)	9 (2,1)	15 (3,8)	-25 (5,0)	14 (1,8)	10 (1,6)
Wind and ice, condition 1	0	3 (1,1)	-3 (1,4)	-16 (0,8)	3 (0,7)	-6 (1,9)
Wind and ice, condition 2	-13 (0,1)	0 (0,1)	-9 (3,9)	-25 (0,8)	-1 (0,2)	-13 (3,8)
Tower FMV 78						
Uniform ice	3 (2,6)	2 (0,3)	3 (1,0)	3 (1,9)	4 (0,4)	3 (0,7)
Non-uniform ice	5 (3,89	16 (1,4)	5 (1,4)	3 (1,6)	5 (0,4)	3 (0,5)
Wind and ice, condition 1	1 (1,4)	2 (0,3)	-1 (0,5)	0 (0,1)	4 (0,4)	-4 (1,0)
Wind and ice, condition 2	-5 (3,6)	0	-8 (2,6)	-8 (3,8)	2 (0,1)	-11 (2,5)

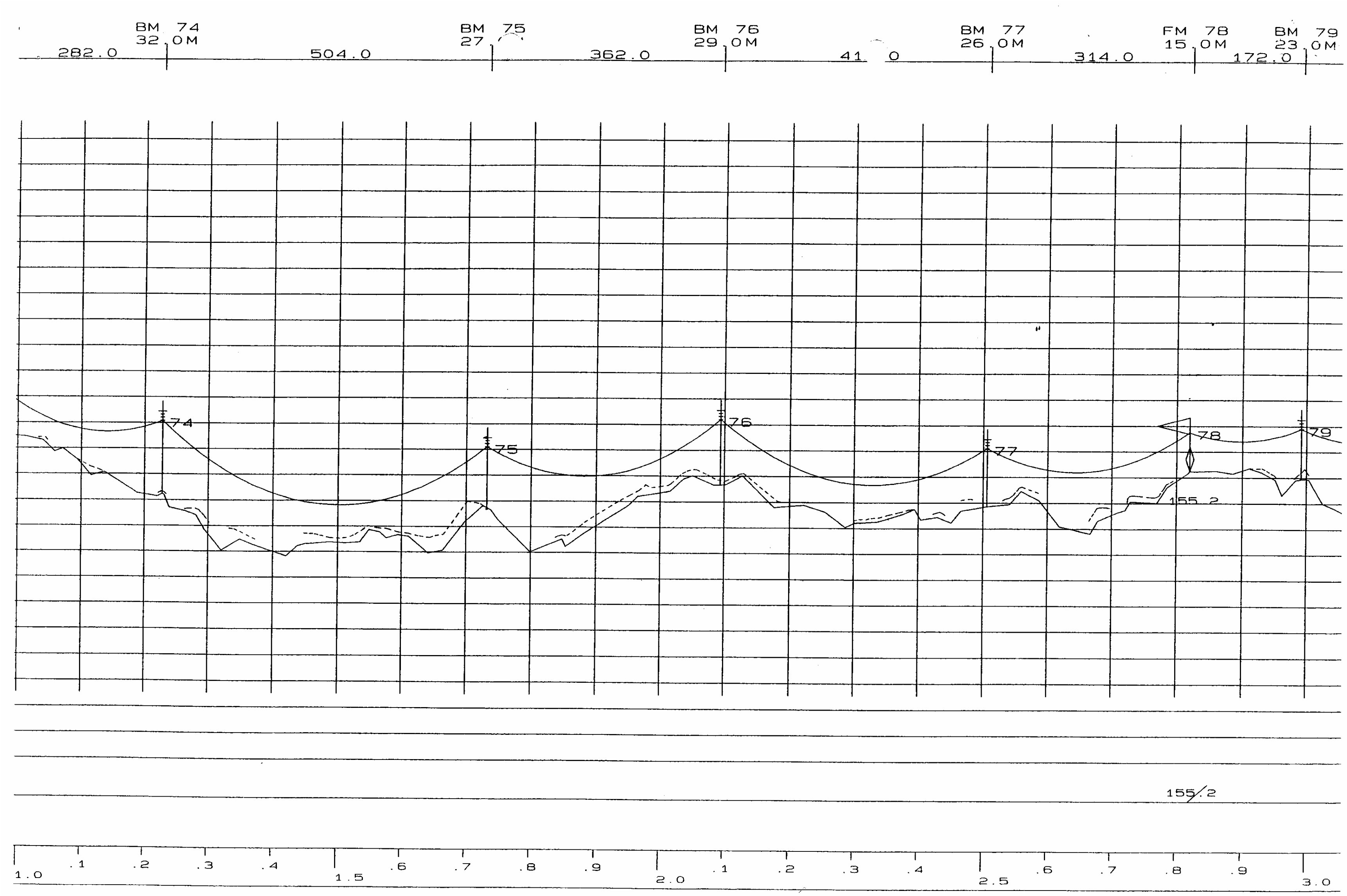
Example profile.

Scale L = 1:5000, H = 1:1250

Definition tower types:
BM = Straight line tower
BMV = Flying angle tower
EM = Dead End tower
FMV = Tension tower (with horiz. angle)

Section	Tower	Horizontal span (meter)	Difference in level (meter)
1	EM 70	297	50
1	BM 71	317	53
1	BM 72	332	7
1	BMV 73	282	-20
1	BM 74	504	-10
1	BM 75	362	11
1	BM 76	412	-12
1	BM 77	314	6
1	FMV 78		
2	FMV 78	172	2
2	BM 79	296	11
2	BM 80	418	-16
2	BM 81	456	26
2	BM 82	340	41
2	BM 83	325	58
2	EM 84		

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32.0M
282.0
504.0
BM 75
27.
362.0
BM 76
29.0M
41 0
BM 77
26.0M
314.0
FM 78
15.0M
172.0
BM 79
23.0M
74
75
76
77
78
79
155.2
155/2
1.0
.1
.2
.3
.4
1.5
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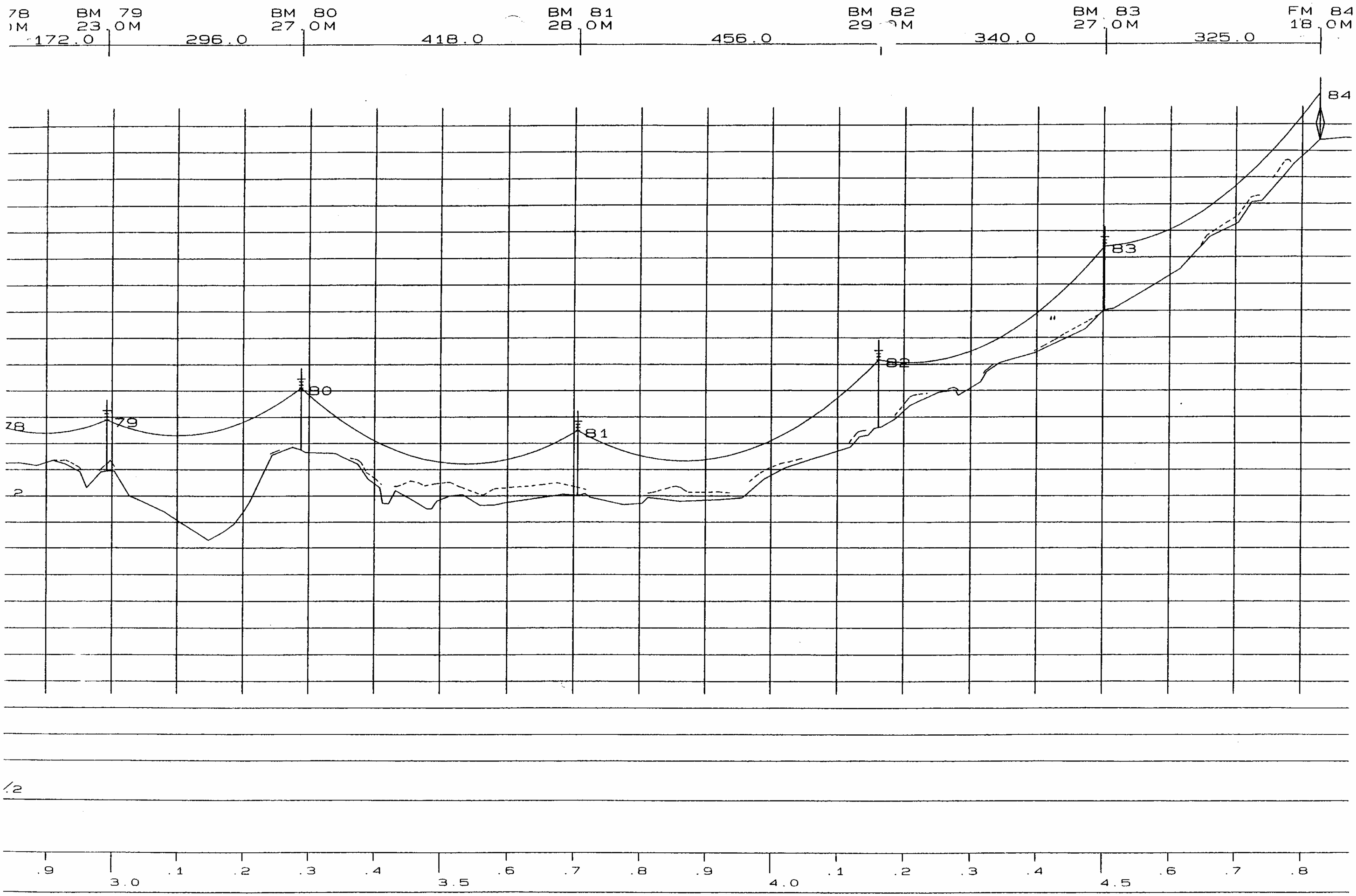
78
BM 79
23.0M
BM 80
27.0M
BM 81
28.0M
BM 82
29 .0M
BM 83
27.0M
FM 84
18.0M
172.0
296.0
418.0
456.0
340.0
325.0
79
80
81
82
83
84
.9
3.0
.1
.2
.3
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3.5
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CIGRE Technical Brochure

Reliability Based Design Methods for Overhead Lines Advantages, Applications and Comparisons

SECTION III - COMPARISONS

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Working Group B2.06

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SECTION III

COMPARISONS BETWEEN IEC 60826 AND OTHER RELIABILITY BASED DESIGN METHODS

1. SCOPE OF SECTION III

Since the publication of Technical Report IEC 826 in 1991, a number of other overhead line design codes based on reliability design (RBD) methods have been published. These documents have generally adopted many of the concepts given in IEC 826, but there are also some *substantial* differences.

The purpose of this Section III is to compare the methods adopted for the calculation of mechanical loadings for overhead power lines according to a number of these design codes with the latest version of the IEC document, IEC 60826 Edition 3 (October 2003).

The main objective is to assess the level of consistency and the significance of any major differences between the different codes.

2. STANDARDS ON RBD

2.1 List of standards compared

IEC 60826	Design Criteria of Overhead Transmission Lines (IEC/TC11/WG08), Ed. 3 issued October 2003 (**IEC**)
CIGRE SCB2	Probabilistic Design of Overhead Transmission Lines (CIGRE Technical Brochure No. 178), February 2001 (**CIGRE**)
EN 50341-1:2001	Overhead Electrical Lines exceeding AC 45 kV – Part 1: General Requirements - Common Specifications (CLC/TC 11), October 2001 (**EN** or **CLC**)
ASCE 74	Guidelines for Transmission Lines Structural Loading (ASCE), Draft as of April 2005 (**ASCE**)
NESC 2002	National Electrical Safety Code 2002 (**NESC**)

2.2 Scope of the standards

International Standard IEC 60826 has been prepared by the IEC Technical Committee 11 Overhead Lines. This standard specifies the loading and strength requirements of overhead lines derived from reliability based design principles. These requirements apply to lines above 45 kV and above, but can also be applied to lines with a lower nominal voltage. It provides a framework for the preparation of national standards dealing with overhead transmission lines, using reliability concepts and employing probabilistic or semi-probabilistic methods. This standard does not cover the detailed design of line components such as supports, foundations, conductors or insulator strings. Although the design criteria apply to new lines, many concepts can be used to address the reliability requirements for uprating and upgrading of existing overhead lines.

CIGRE Working Group WG B2.06 “Principles of Overhead Lines” contributed to the review of the IEC 60826 standard with the CIGRE Technical Brochure 109 and with the Companion Document CIGRE Technical Brochure 178.

European Standard EN 50341 has been drawn up by the Technical Committee CENELEC TC 11. This standard specifies the general requirements that shall be met for the design and construction of new overhead lines to ensure that the line is suitable for its purpose with regard to safety of persons, maintenance, operation and environmental considerations. EN 50341 also covers the detailed design of overhead line components. It applies to overhead electric lines with rated voltages exceeding 45 kV AC. CENELEC prepared a complementary standard for lower voltage levels.

Beside the clauses that are common to all European countries (Main Body or EN 50341-1), this standard also includes National Normative Aspects (NNA or EN 50341-3) that are normative to the country considered, such as A-deviations (required by the existing national laws or regulations), Special National Conditions (SNC or national characteristics or practices that cannot be changed even over a long period, e.g. those due to climatic conditions) and National Complements (NCPT or national practices that should be gradually adapted to the Main Body). Both deterministic (called "Empirical") and probabilistic (called "General" or "Statistical") approaches are considered in the Main Body. Each National Committee can further decide to use either the Empirical or the General Approach.

North-American Standard ASCE 74 has been prepared by the Task Committee on Structural Loadings of the Committee on Electrical Transmission Structures of the American Society of Civil Engineers (ASCE). ASCE 74 provides detailed guidelines and procedures for developing transmission line structure loads. As this manual is intended as a loading document, it contains almost no discussion of strengths except in most general terms and to note the differentiation between limit states and damage limits when discussing the problems of the application of reliability based design concepts. Although intended as a guide for lines 69 kV and above, the application of the concepts in this standard might be justified at lower voltages.

The purpose of the **Safety Code NESC 2002** is the practical safeguarding of persons during the installation, operation or maintenance of electric supply and communication lines and associated equipment. The NESC 2002 contains the basic provisions that are considered necessary for safety of employees and the public under the specified conditions. The NESC is not intended as a design specification or as an instruction manual.

2.3 Comparison of some EN-NNA

A comparison of the wind loadings calculated in accordance with the General (or Statistical) Approach of CENELEC National Normative Aspects documents produced by the National Committees of the following countries is included in Appendix A:

EN 50341-3-7	Finland	**(NNA/FI)**
EN 50341-3-9	Great Britain	**(NNA/UK)**
EN 50341-3-16	Norway	**(NNA/NO)**
EN 50341-3-18	Sweden	**(NNA/SE)**
EN 50341-3-19	Czech Republic	**(NNA/CZ)**

2.4 Comparison of symbols and definitions

The symbols adopted in this document are those used in the various documents listed above, but it should be noted that usage varies across the range of documents. Brief definitions of symbols are included in this paper, but for full details reference should be made to the appropriate document. It should also be noted that some parameters which are given similar titles or symbols in different documents are defined differently. Where possible, preference is given to the symbols and definitions of IEC 60826.

2.5 Comparison of line components and subsystems

An overhead line is designed as a system made of separate components (IEC, CIGE, EN) or subsystems (ASCE, NESC).

Table 2.5 – Overhead Line components and subsystems

IEC, CIGRE, EN	ASCE, NESC
Component	Subsystem
Support	Support system
Foundation	
Conductor and earthwire	Wire system
Insulator string	

3. BASIS OF DESIGN

Table 3.1 **Basis of design**	IEC, CIGRE	EN	ASCE	NESC
Reliability requirements – Reliability levels – Relative reliability factors Return period T (years) of climatic load (1) (2)	Yes 3 – 50, 150, 500	Yes 3 – 50, 150, 500	Yes – 4 50, 100, 200, 400	Yes 1 - 50
Security requirements (3)	Yes	Yes	Yes (4)	Yes (5)
Safety requirements (6)	Yes	Yes	Yes	Yes
Strength coordination	Yes	Yes (7)	Yes (7)	No
Limit state for: – Reliability (probabilistic) – Security (deterministic) – Safety (deterministic)	 Damage Failure Damage	 Ultimate Ultimate Ultimate	 Damage Failure Damage	 Ultimate Ultimate Ultimate

Notes:

(1) Reference return period is usually 50 years

(2) Also called **limit load** in IEC/CIGRE, **characteristic** or extreme load in EN and weather-related design load for return period in ASCE

(3) To reduce risk of uncontrollable propagation of failures

(4) Dynamic longitudinal load factors and Residual Static Load (RSL) factors are provided.

(5) Concept stated only. No specific requirements, or guidance for calculation of security loadings is given.

(6) To ensure safe construction and maintenance conditions

(7) General guidance only provided for strength coordination

4. BASIC DESIGN EQUATION

Table 4.1 – Basic design equation

Code	Design limit load	< Design strength
IEC, CIGRE	Effect of Q_T [1] or effect of $\gamma_T \cdot Q_{50}$	$< Ø_S \cdot Ø_N \cdot Ø_Q \cdot Ø_C \cdot R_C$ [2]
EN	Effect of $\gamma_F \cdot F_{50}$ or effect of F_T	$< R_K / \gamma_M$ [3]
ASCE	Effect of $\gamma \cdot Q_{50}$ or effect of Q_{RP}	$< Ø \cdot R_n$ [4]
NESC [5] Extreme wind District Loads	 L_{50} $OLF \cdot L$ [6]	 $< Ø \cdot R_n$ $< Ø \cdot R_n$ [7]

The nomenclature varies between the various documents.

Q_T, F_T, Q_{RP} and L_{RP} are defined as climatic loads (weather-related loads for ASCE/NESC) having a return period T (RP for ASCE/NESC).

γ, γ_T, γ_F are load factors applied to loads having a reference return period. They are given in Clauses 6.1 to 6.7.

R_C, R_K and R_n are defined as the **characteristic strength** (IEC/CIGRE, EN) or the **nominal strength** (ASCE, NESC) specified in appropriate standards, also called **guaranteed strength** or minimum strength (or minimum failing load for IEC and percentage of an estimated breaking load for ASCE). This value corresponds usually to an exclusion limit of 2% to 5% (i.e. the value being reached with a 98% to 95% probability). When not specified or calculated, the exclusion limit is conservatively taken as 10% (or with 90% probability). ASCE recommends that in the future all transmission and distribution line strength design guides publish strength values at the 5% lower exclusion limit.

Notes:

(1) Q_T can be obtained from the statistical analysis of climatic data. If only Q_{50} is available Q_T can be estimated by multiplying Q_{50} by load factor γ_T (or γ_{Tw}^2 if the adjustment factor for the wind speed is γ_{Tw}).

(2) $Ø_S$, $Ø_N$, and $Ø_Q$ are strength factors (IEC/CIGRE) depending on strength coordination (see Clause 7.2), number of components, and quality level respectively. $Ø_C$ takes account of

variation between the actual exclusion limit of characteristic strength, R_C, and the supposed 10% exclusion limit. Values of Ø are usually less than 1.0.

(3) γ_M is the partial factor (EN) for material property covering unfavourable deviations from characteristic strength, R_K, inaccuracies in applied conversion factors and uncertainties in the geometric properties and the resistance model.

(4) Ø is a strength factor (ASCE) that takes account of strength coordination (see Clause 7.2) and variation between nominal strength, R_n, and the (5%) exclusion value, R_e. Values of Ø are usually less than 1.0.

(5) The current NESC 2002 has an extreme wind load case, probabilistic based on a 50 return period. For this extreme wind load there is only one level for line reliability. The NESC also consider District Loads. These loads are deterministic and summarized in Table 4.2 below.

(6) OLF is the Overload Factor (NESC) to be applied to the District loads.

(7) Ø is a strength factor (NESC) that takes into account of the variability of material and deterioration after installation.

Table 4.2 – Characteristics of deterministic District Loads (NESC)

District Load L	Wind pressure Pa	Ice thickness mm	Temperature °C
Light	430	0	-1
Medium	190	6.5	-10
Heavy	190	12.5	-20

5. COMBINATION OF LOADS

Table 5.1 - Loading Condition	IEC	CIGRE	EN	ASCE	NESC
Reliability Based Design Conditions	X	X	X	X	X
Limit wind load at reference temperature	X	X	X	X	X
Reduced wind load at low temperature	X	X	X	X	-
Uniform ice loads on all spans	X	X	X	X	-
Unbalanced ice loads, longitudinal bending	X	X	X	X	X
Unbalanced ice loads, torsional bending	X	X	X	(X)	(X)
LP ice load and moderate wind load	X	X	X	X	D
LP wind load and moderate ice load	X	X	X	-	-
LP drag, moderate wind and ice load	X	X	-	-	-
Deterministic Security Conditions					
Torsional loads	X	-	(X)	(X)	(X)
Longitudinal loads	X	-	(X)	(X)	(X)
Deterministic Safety Conditions					
Construction loads	X	-	(X)	(X)	(X)
Maintenance loads	X	-	(X)	(X)	(X)

Notes:

LP	Low probability (having a high return period T)
X	The load combination is specified in the document; bases for the calculation of loadings are given.
(X)	The load combination is specified in the document, but only general guidance is given.
D	Deterministic condition

6. LOAD FACTORS FOR PERMANENT AND VARIABLE LOADS

6.1 Load factors for dead loads

Table 6.1 – Load factors for dead loads

Code	Reliability Based Design Cases	Deterministic Load Cases
IEC, CIGRE	1.0	-
EN	1.0	-
ASCE	1.1	Security: 1.0 Safety: 1.5
NESC		
Extreme wind	1.0	-
District Loads	-	Metal Grade B: 1.50; Metal Grade C: 1.90

6.2 Load factors for wind loads

Table 6.2 - Load factors for wind loads

Reliability level Return period T (years)	1 50	2 150	3 500
IEC, CIGRE (1)(2)	(Q_{50}) 1.00	$(Q_{150}=1.10^2\ Q_{50})$ 1.21	$(Q_{500}=1.20^2\ Q_{50})$ 1.44
EN (3)	1.00	1.20	1.40

Reliability factor Return period RP (years)	1 50	2 100	4 200	8 400
ASCE (4)(5)	1.00	1.15	1.30	1.45

NESC	Grade B	Grade C
Extreme wind	1.00	1.00
District loads	2.50	2.20
(Wire Tension)	(1.65)	(1.30)

Notes:

(1) Default load factors (IEC, CIGRE) are based on coefficient of variation (COV) up to 0.16 for wind speed and are derived from the Gumbel distribution function.

(2) IEC has an additional return period of 25 years for use with temporary structures.

(3) Load factor (EN) is depending on the selected reliability level and takes account of the possibility of unfavourable deviations from the characteristic load values, inaccurate modelling and uncertainties in the assessment of the load effects. The COV is not specified.

(4) Load factors (ASCE) are based on coefficient of variation (COV) up to 0.18 for wind speed and are derived from the Gumbel distribution function.

(5) ASCE has an additional return period of 25 years for use with temporary structures. The relative reliability factor is 0.5.

6.3 Load factors for ice loads

Table 6.3 - Load factors for ice loads
(Load factors may be applied either to ice thickness or to the weight of ice per unit length of conductor)

<table>
<tr><td>Reliability level
Return period T (years)</td><td colspan="4">1
50</td><td colspan="4">2
150</td><td colspan="4">3
500</td></tr>
<tr><td>IEC, CIGRE
Ice thickness (2)
Ice weight (2)</td><td colspan="4">(Q_{50})
1.00
1.00</td><td colspan="4">(Q_{150}) (1)
1.15
1.20</td><td colspan="4">(Q_{500}) (1)
1.30
1.45</td></tr>
<tr><td>EN: Ice weight (3)</td><td colspan="4">1.00</td><td colspan="4">1.25</td><td colspan="4">1.50</td></tr>
<tr><td>Reliability level
Return period RP (years)</td><td colspan="3">1
50</td><td colspan="3">2
100</td><td colspan="3">4
200</td><td colspan="3">8
400</td></tr>
<tr><td>ASCE (4)(5): Ice thickness</td><td colspan="3">1.00</td><td colspan="3">1.25</td><td colspan="3">1.50</td><td colspan="3">1.85</td></tr>
<tr><td>NESC</td><td colspan="6">Grade B</td><td colspan="6">Grade C</td></tr>
<tr><td>Vertical loads
(metal structures)</td><td colspan="6">1.5</td><td colspan="6">1.5</td></tr>
</table>

Notes:

(1) If values of Q_{150}, and Q_{500} are available from statistical analysis, these may be adopted.

(2) Default load factors are based on COV up to 0,30 for ice thickness and COV up to 0,65 for unit ice weight and are derived from the Gumbel distribution function

(3) Load factor (EN) is depending on the selected reliability level and takes account of the possibility of unfavourable deviations from the characteristic load value, inaccurate modelling and uncertainties in the assessment of the load effects. The COV is not specified.

(4) The ice loads are according to the revised ASCE 7-02 (ASCE 2002) ice load map. The COV is not specified.

(5) ASCE has an additional return period of 25 years for use with temporary structures. The relative reliability factor is 0.5.

6.4 Combination factors for moderate loads

Table 6.4 - Combination factors for moderate loads

Code	Wind load (with low probability ice)	Ice load (with low probability wind)
IEC, CIGRE	Average of yearly maximum (Q_1)	Average of yearly maximum (Q_1)
EN	0.40 for 3 year return value (Q_3)	0.35 for 3 year return value (Q_3)
ASCE	X (1)	-
NESC	-	-

Note:

(1) ASCE wind speeds concurrent with the 50-year ice thicknesses are back-calculated using the 50-year wind-on-ice load on a 1-inch wire and the 50-year ice thickness. The concurrent wind speed is not adjusted for other return periods of extreme ice load.

6.5 Other load factors

Table 6.5 – Other load factors

Code	Wind load at low temperature (Min yearly temperature with return period T)	Security load (1)	Safety load (1) Construction and maintenance loads
IEC	$0.6^2 = 0.36$	1.0	1.5 (if careful works)
CIGRE	–	-	-
EN	not specified	1.0	1.5
ASCE	-	1.0	1.5
NESC	-	-	-

Note:

(1) Security and Safety loadings are deterministic in nature and their magnitude is independent of reliability level.

7. WIND LOADS

7.1 Terrain roughness

IEC, CIGRE, ASCE and NESC define the roughness factor K_R, the roughness coefficient α for one, three or four different terrain categories. EN defines the terrain factor k_T and the ground roughness parameter z_O. The following definitions and values in Table 7.1 are used.

Table 7.1 – Terrain categories

Terrain Category	Roughness characteristic	Code	Value	
			K_R	α
A	Large stretch of water upwind, flat coastal areas	IEC, CIGRE	1.08	(0.10-0.12)
I	Rough open sea, lakes with at least 5 km fetch upwind and smooth flat country without obstacles	EN	$k_T = 0.17$	$z_0 = 0.01$
D	Flat unobstructed areas directly exposed to wind flowing over open water (excluding shorelines in hurricane prone regions for a distance of at least 1.6 km)	ASCE	1.09	0.09
B	Open country with very few obstacles, airports or cultivated fields with few trees and buildings	IEC, CIGRE	1,00	(0.16)
II	Farmland with boundary hedges, occasional small farm structures, houses or trees	EN	$k_T = 0.19$	$z_0 = 0.05$
C	Open terrain with scattered obstructions	ASCE (NESC)	1.00	0.11
C	Terrain with numerous small obstacles of low height (hedges, trees and buildings)	IEC, CIGRE	0.85	(0.22)
III	Suburban or industrial areas and permanent forests	EN	$k_T = 0.22$	$z_0 = 0.30$
B	Urban and suburban areas, well-wooded areas, or terrain with numerous closely spaced obstructions having the size of single-family dwellings or larger	ASCE	0.85	0.14
D	Suburban areas or terrain with many tall trees	IEC, CIGRE	0.67	(0.28)
IV	Urban areas in which at least 15% of the surface is covered with buildings with mean height > 15 m	EN	$k_T = 0.24$	$z_0 = 1.0$
V	Mountainous and more complex terrain where the wind may be locally strengthened or weakened	EN	shall be evaluated separately possibly by meteorologists	

7.2 Reference wind speed V_R

The reference wind speed (basic wind speed for ASCE/NESC) is defined as the wind speed measured at a height of 10 m above ground level, corresponding to an averaging period of 10 min (mean wind speed for IEC, CIGRE and EN) or 3 seconds (gust wind speed for EN, ASCE and NESC) and having a return period T (RP for ASCE).

Table 7.2 – Reference wind speed V_R
(10 m height; return period T)

Code	Gust wind speed (Average period of 3 s)	Mean wind speed (Average period of 10 min)
IEC, CIGRE	-	V_R
EN	$V_R = V_g$	$V_R = V_{mean}$
ASCE	V_{RP}	-
NESC Extreme wind	V_{RP}	-

Reference wind speed V_R (basic wind speed V_{RP} for ASCE) measured in weather stations typical of open flat terrain, such as airports (terrain category B for IEC and CIGRE; II for EN; C for ASCE and NESC), is identified as V_{RB} ($V_{R(II)}$ for EN and V_{RP} for ASCE and NESC). Where available wind data differ from these assumptions, conversion methods are provided in the Codes. These methods are discussed in the next Clauses.

7.3 Variation of wind speed with terrain category and height

For the purpose of this document the original equations for the variation of the wind speed with terrain category and height above ground, z, have been split into two independent parts K_R and K_h (Table 7.3) where:

$K_R = V_R / V_{RB}$

$K_h = V_h / V_R$

K_R represents a multiplier for the conversion of the reference wind speed for terrain category B, V_{RB} to V_R for other terrain categories than B.

K_h represents a multiplier for the conversion of the wind speed for z = 10 m height above ground, V_R to V_h for other heights than 10 m.

Finally V_h may be obtained from:

$V_h = K_h \,.\, V_R = K_R \,.\, K_h \,.\, V_{RB}$

Table 7.3 – Variation of wind speed with terrain category and height

Code	Original equation for $V_h / V_{RB} = K_R \,.\, K_h$	K_R	K_h
IEC, CIGRE	$K_R\ (z/10)^{\alpha}$	K_R	$(z/10)^{\alpha}$
EN	$k_T \ln (z/z_0)$	$k_T \ln (10/z_0)$	$\ln (z/z_0) / \ln (10/z_0)$
EN (alternative)	$K_R\ (z/10)^{\alpha}$	K_R	$(z/10)^{\alpha}$
ASCE	$(K_Z)^{1/2} = K_R\ (z/10.06)^{\alpha}$	K_R	$(z/10.06)^{\alpha}$

All Codes apply the so-called “power law” for the variation of the wind speed with height, except EN that uses an alternative wind model (logarithmic law where k_T and z_0 are given in Table 7.1).

For the purpose of this document the original equation of ASCE:

$K_Z = 2.01\ (z(\text{ft}) / z_g(\text{ft}))^{2\alpha}$

(where z_g is 700 ft, 900 ft and 1200 ft and α is 1/11.5, 1/9.5, 1/7.0 for respectively ASCE terrain category D, C and B) has been converted in metric units:

$(K_Z)^{1/2} = K_R\ (z/10.06)^{\alpha}$

where K_R and α are found in Table 7.1.

K_R and K_h are not formally used in the original equations of EN (k_T and z_0 are used) and ASCE (K_Z is used). Moreover K_h is integrated in the combined wind factor of IEC (See Clause 7.5).

7.4 Relative wind speed

The relative wind speed $V_h / V_{RB} = K_R.K_h$ is given in Table 7.4 for IEC terrain categories A, B, C and D and for heights above ground, z, of respectively 10 m, 30 m and 50 m. The relative wind speed V_h / V_{RB} equals K_R for z = 10 m.

Table 7.4 – Relative wind speed

Height in m	$V_h / V_{RB} = K_R.K_h$	Code	Terrain category to IEC			
			A	B	C	D
10	K_R	IEC, CIGRE EN ASCE	1.08 1.17 1.09	1.00 1.00 1.00	0.85 0.77 0.85	0.67 0.55 -
30	$K_R.K_{30\ m}$	IEC, CIGRE EN ASCE	1.20-1.23 1.36 1.20	1.19 1.22 1.12	1.08 1.01 0.99	0.91 0.82 -
50	$K_R.K_{50\ m}$	IEC, CIGRE EN ASCE	1.27-1.31 1.45 1.25	1.54 1.31 1.19	1.21 1.13 1.07	1.05 0.94 -

7.5 Unit action of wind speed on any component of the line

The following expressions are used for the unit action, a, of the wind speed on any line component:

IEC/CIGRE $a = ½.\mu.K_R^2.V_{RB}^2.C_X.G$

- μ air mass density $^{(1)}$
- K_R roughness factor at the line location (see Clause 7.1)
- V_{RB} reference wind speed at flat and open terrain category B
- C_X drag coefficient for the component X being considered
- G combined wind factor depending on height above ground, wind gust, dynamic response and terrain category

EN $a = ½.\rho.K_R^2.K_h^2.(V_{R(II)})^2.C_X.G_X.G_q$

- ρ air mass density $^{(1)}$
- K_R terrain factor at the line location (see Clause 7.3)
- K_h takes into account height effect for $V_{R(II)}$ (see Clause 7.3)
- $V_{R(II)}$ reference wind speed at flat and open terrain category II
- C_X drag factor for the component X being considered
- G_X structural resonance factor for the component X being considered
- G_q gust response factor depending on height above ground and terrain category (equals 1 if the gust wind speed is considered)

ASCE $a = ½.\rho.K_Z.V_{RP}^2.C_f.G.K_{zt}$

- ρ air mass density$^{(1)}$
- K_Z velocity pressure exposure coefficient which takes into account terrain category and height above ground (see Clause 7.3)
- V_{RP} basic wind speed at flat and open terrain category C
- C_f force (i. e. drag) coefficient for the component being considered
- G gust response factor including span effect, depending on height above ground and terrain category (This gust factor is derived from the Davenport model and ASCE neglects the resonant component of this model)
- K_{zt} optional factor to account for terrain effects from mountains and hills

NESC $a = \frac{1}{2}.\rho.K_Z .V_{50}^2.I.C_d.G$ (only for the extreme wind condition)

· ρ	air mass density (1)
· K_Z	velocity pressure exposure coefficient which takes into account height above ground for terrain category C
· V_{50}	basic wind speed at flat and open terrain category C
· I	importance factor, 1.0 for utility structures and their support facilities
· C_d	force (i. e. drag) coefficient for the component being considered
· G	gust response factor including span effect, depending on height above ground and terrain category (This gust factor is derived from the Davenport model and ASCE neglects the resonant component of this model)

Note:

(1) The air mass per unit volume is equal to 1.225 kg/m^3 (1.226 kg/m^3 for ASCE) at a temperature of 15 °C and an atmospheric pressure of 101,3 kPa at sea level. All Codes provide an air density correction factor when the temperature and the altitude are significantly different from the assumptions.

7.6 Comparison of combined wind factors for conductors

The combined wind factor, G, for conductors which takes account of gust effects (dependant on span length), conductor height above ground and terrain category is compared in this clause with the following parameters.

- $G_c.G_L$ of the IEC, CIGRE document, where G_c is the combined wind factor for conductors with a span length of 200 m and G_L is the span factor ($G_L = 1.0$ for a span length of 200m)
- $K_h^2.G_q.G_{Xc}$ of the EN code, where G_q is the gust response factor and G_{Xc} the resonance factor for the conductor, also termed “span factor”
- $K_h^2.G_w.K_v^2$ of the ASCE/NESC code, where G_w is the gust response factor for conductors (wires) including span effect for wires. To make this value comparable it is multiplied by $K_v^2 = (V_{3\ s}/V_{10\ min})^2 = 1.43^2 = 2.04$, to take in account the reference to the 10 minute average wind speed

Table 7.6a - Comparison of combined wind factors for conductors at terrain category B

Height in m	Code	Span length in m		
		200	400	600
10	IEC, CIGRE EN ASCE/NESC	1.84 1.94 1.51	1.73 1.77 1.39	1.624 1.72 1.31
30	IEC, CIGRE EN ASCE/NESC	2.25 2.32 1.81	2.12 2.17 1.68	1.99 2.08 1.61
50	IEC, CIGRE EN ASCE/NESC	2.44 2.60 1.96	2.30 2.43 1.84	2.16 2.33 1.76

Table 7.6b - Height considered for conductors

Code	Theoretical height	Location	For support calculation
IEC	Centre of gravity	Lower third of sag	Attachment point of (middle) conductor
CIGRE	-	Lower third of sag	-
EN	Centre of wind pressure	-	-
ASCE	Centre of wind pressure	Higher third of sag (for no wind)	-
NESC	-	Height of wire at structure	-

7.7 Comparison of combined wind factors for towers

The combined wind factor, G, for lattice towers (depending on gust, height and terrain category) as used by IEC, CIGRE (TB109), is compared in this clause with the following parameters:

- G_t of the IEC/CIGRE document, where G_t is the combined wind factor for towers
- $K_h^2 . G_q . G_{Xt}$ of the EN code, where G_{Xt} is the drag factor for the tower (G_{Xt} taken as 1.0)
- $K_h^2 . G_t . K_v^2$ of the ASCE code, where G_t is the gust response factor for the tower. To make this value comparable it is multiplied by $K_v^2 = (V_{3\ s}/V_{10\ min})^2 = 1.43^2 = 2.04$, to take in account the reference to the 10 minute averaging wind speed

Table 7.7 - Comparison of combined wind factors for towers

Height in m to CG of panel (1)	Code	IEC Terrain category			
		A	B	C	D
10	IEC CIGRE EN ASCE NESC	1.70 1.70 1.69 1.70 -	1.95 1.95 1.94 1.90 1.90	2.50 2.55 2.38 2.26 -	3.30 3.30 3.96 - -
30	IEC CIGRE EN ASCE NESC	1.95 2.00 2.06 1.92 -	2.32 2.30 2.51 2.16 2.16	2.95 3.00 3.01 2.60 -	3.95 3.90 4.48 - -
50	IEC CIGRE EN ASCE NESC	2.15 2.15 2.29 2.02 -	2.55 2.50 2.86 2.28 2.28	3.35 3.25 3.69 2.76 -	4.40 4.40 7.50 - -

Note:

(1) The height above ground level is measured at the centre of gravity (CG) of the panel.

8. DRAG COEFFICIENTS

For conductors in IEC, CIGRE, EN, ASCE and NESC the recommended drag coefficient or factor C_X = 1,0 (1.0 to 1.4 for wires covered with glaze ice).

For lattice towers in IEC, CIGRE and EN the same magnitude for the drag coefficient is recommended, depending on the solidity ratio.

In ASCE slightly different values are given see Figure 1.

In NESC, the drag coefficient is 1.6 for lattice with a tower face shielding factor of 2.0.

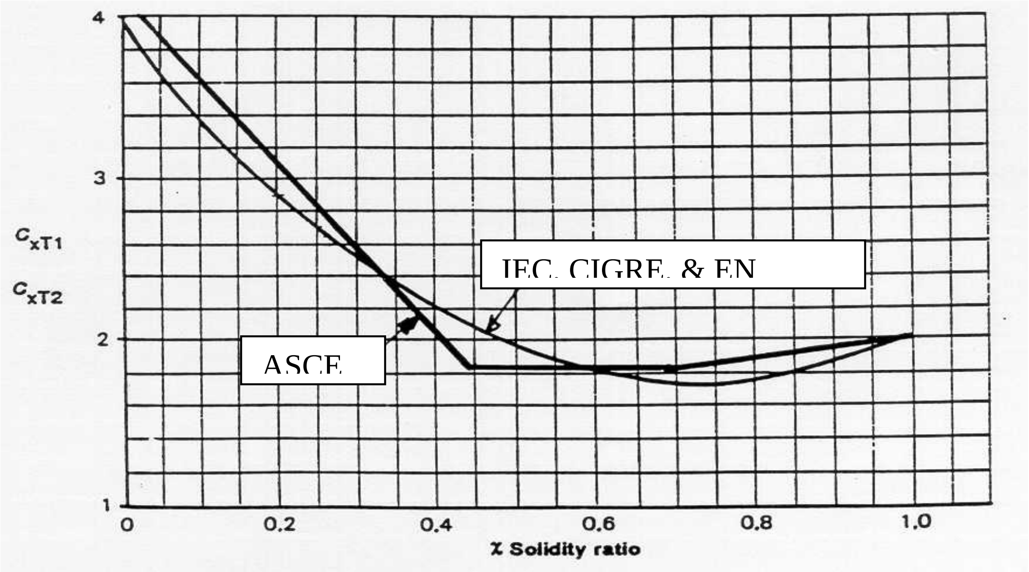

Figure 1. - Drag coefficient for lattice towers

9. SPAN FACTOR

In Figure 2 the span factor is given in the different codes is shown.

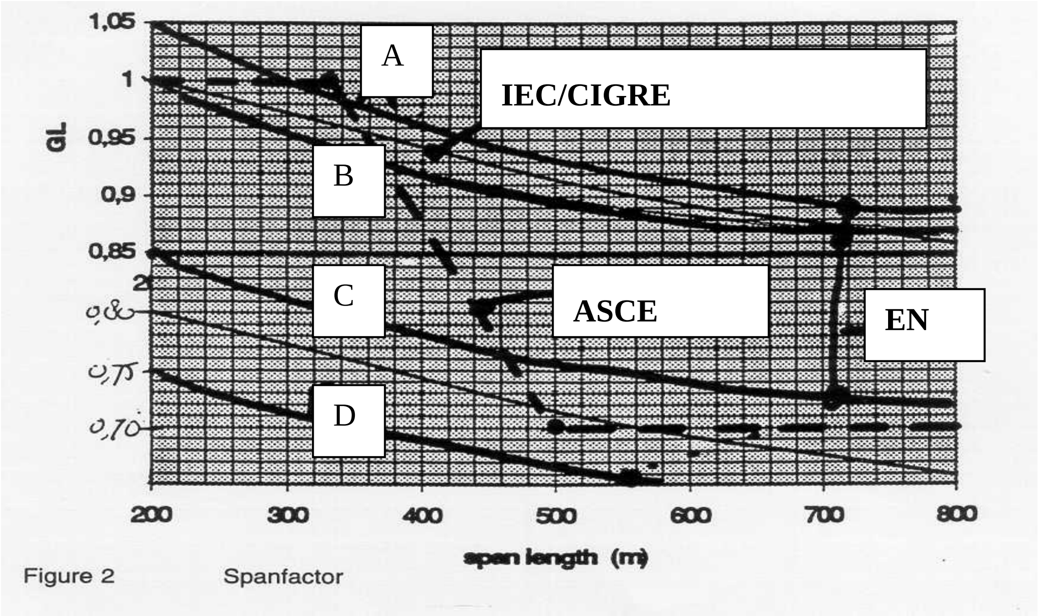

Figure 2. - Span factor for conductors

10. ICE LOADS

In IEC, CIGRE and EN the basic ice load, g (N/m), is referred to a conductor of diameter 30 mm 10 m above the ground. In ASCE/NESC reference is not given.

Table 10.1 - Comparison of reference ice loads

Code	Ice variable	Adjustment factors	
		Diameter (K_d)	Height (K_h)
IEC	weight	X	X(1)
CIGRE	weight thickness	X X	X(1) X(1)
EN	weight	X(2)	-
ASCE	thickness (3)	-	X(1)
NESC	thickness	-	-

Notes:

(1) only for precipitation icing

(2) no values specified

(3) factor K_{zt} in the unit action equation for ASCE (see Clause 7.5) has to be replaced by $K_{zt}^{0.35}$ for ice loading

Table 10.2 - Comparison of unbalanced ice load condition

Code	Longitudinal bending	Transversal bending	Torsional bending
IEC	$\alpha_1 = 0{,}28$, $\alpha_2 = 0{,}7$	$\alpha_1 = 0{,}28$, $\alpha_2 = 0{,}7$	$\alpha_1 = 0{,}28$, $\alpha_2 = 0{,}7$
CIGRE (TB 109)	$\alpha_1 = 0{,}28$, $\alpha_2 = 0{,}7$	$\alpha_1 = 0{,}28$, $\alpha_2 = 0{,}7$	$\alpha_1 = 0{,}28$, $\alpha_2 = 0{,}7$
EN	$\alpha_1 = 0{,}30$, $\alpha_2 = 0{,}7$	$\alpha_1 = 0{,}50$, $\alpha_2 = 1{,}0$	$\alpha_1 = 0{,}30$, $\alpha_2 = 0{,}7$
ASCE	Mentioned but no values given	Mentioned but no values given	Mentioned but no values given
NESC	Mentioned but no values given	-	-

11. COMBINED WIND AND ICE LOADS

See Clauses 5 and 6.4. The equivalent of ice-covered conductors is defined the same as in IEC, CIGRE, EN and ASCE.

Table 11.1 - Comparison of drag coefficient and densities (kg/m^3)

Code		Precipitation	In-cloud ice	In-cloud ice	Precipitation
		Wet snow	Soft rime	Hard rime	Glace ice
IEC	Drag Density	1.0 600	1.2 600	1.1 900	1.0 900
CIGRE	Drag Density	1.0 / 1.4 600 / 400	1.2 / 1.7 600 / 400	1.1 / 1.5 900 / 700	1.0 / 1.4 900 / 900
EN	Drag Density	1.0 500	1.2 300	1.1 700	1.0 900
ASCE	Drag Density	1.0 600 / 800	1.0 150	1.0 900	1.0 900
NESC	Drag Density	- -	- -	- -	1.0 900

12. FAILURE AND CONTAINMENT LOADS (SECURITY LOADS)

IEC, CIGRE, EN, ASCE and NESC define the torsional and longitudinal loads.

The guidelines given in these codes are in principle the same.

IEC and CIGRE provide guidelines for additional security for specific situations.

13. CONSTRUCTION AND MAINTENANCE LOADS (SAFETY LOADS)

IEC, CIGRE, EN, ASCE and NESC provide guidelines for construction and maintenance loads.

14. STRENGTH COORDINATION

It is generally ensured that foundations are more reliable than their supports. The strength levels of the supports and the foundations can be adjusted relative to each other.

ASCE 74 considers that the question of relative reliability can be solved by the selection of strengths at appropriate exclusion limits or, equivalently, by the application strength factors. It is considered sufficient that matching the 10% exclusion limit of the strength of supports to the 1% exclusion limit of the strength of foundations, will ensure sufficient separation that the supports will fail before their foundations.

In order to achieve strength coordination, IEC 60826 recommends to apply a strength reduction factor $Ø_{S2}$ to the strength of the component (foundation) chosen to be more reliable while a factor $Ø_{S1} = 1.0$ is applied to the first component to fail (support). IEC 60826 provides a statistical method to derive the strength factor $Ø_{S2}$ for various combinations of the coefficient of variation (COV) of the strength of foundations (usually 0.10 to 0.30) and suspension supports (usually 0.05 to 0.10) so that the foundation will fail after the support with a target probability of 90%.

15. OTHER LOADS

EN provides additional guidelines for loads caused by:

- Short-circuit
- Avalanches
- Earthquakes

ASCE provides additional guidelines for loads caused by:

- Conductor galloping
- Flooding
- Structural vibration
- Earthquakes
- High Intensity Winds

NESC provides additional guidelines for loads caused by:

- Earthquakes

High Intensity Winds (HIW) do not follow the pattern and characteristics of extreme wind from which the gust response factors are developed. ASCE considers that the probability of a transmission line being crossed by a tornado is significant. 86% of the tornadoes observed in a 63-year period and categorized by F scale are assigned to the scale of F2 (gust wind speed range from 180 km/h to 253 km/h; path width: 52 m to 162 m; path length: 5 km to 16 km) or smaller. The path width may be sufficient to create very large loads acting on the structure but the conductor loads on the full span will be much smaller. Tornado loading applied to the wire system is neglected for the small tornado widths of F2. For this case, it is appropriate to consider the load factor, γ, the gust response factor, G_t and the velocity pressure exposure coefficient, K_Z, equal to 1.0.

For severe types of tornadoes, the line designers focus changes from resisting the HIW to one of failure containment.

16. GENERAL OVERVIEW

All the documents considered share many common features. All adopt a reliability based (i.e. probabilistic or semi-probabilistic) design method for calculation of climatic loads, essentially similar to IEC 60826. However, the European Standard EN 50341-1 still provides a deterministic "Empirical Approach" as an alternative for some countries.

IEC 60826 and ASCE 74 adopt alternative limit states of "damage", for use with reliability based and safety loadings, and "failure" for use with security loading cases. The other documents use "ultimate" limit state for all these loading cases.

Climatic loadings tend to be the most important in the design of overhead lines, but all documents also give guidance on security loading cases and construction and maintenance load cases to be used for design. Neither security nor construction and maintenance loadings lend themselves completely to a reliability-based approach. In most documents security loading cases are based on arbitrary assumptions about hypothetical broken conductors causing unbalanced longitudinal occurring. These conditions are combined with climatic loadings based on low return periods.

There are minor differences in the formulation of the basic design equations, but climatic loadings are always based on weather events of a specified return period, usually 50 years (See Table 4.1).

The range of loading cases considered differs between the various Codes, with IEC offering the most extensive range (See Table 5.1).

For load factors on wind loadings, IEC applies factors to wind speed. The other documents apply factors to wind load or pressure factors (Table 6.2). For ice loading, IEC and ASCE offer alternative approaches of applying factors to ice thickness. IEC and EN apply factors to ice weight (Table 6.3).

For combinations of weather events occurring simultaneously, for example wind and ice loading, all documents assume that improbable events will not occur simultaneously, i. e. the maximum ice loading based on a 50 year return or higher return period event would occur simultaneously with a wind loading of much lower return period and vice-versa (See Tables 6.4 and 6.5).

The terrain categories and defining parameters used in the different codes are listed in Table 7.1 and the nearest equivalents between the different codes are grouped together. It should be noted that the subsequent wind loading calculations are based on Terrain Type B to IEC, taken as equivalent to Category II in EN or Category C in ASCE/NESC.

IEC and EN take a reference wind speed based on a 10 minute mean wind speed, whereas ASCE/NESC adopt a 3 second gust wind speed (Table 7.2).

For the purpose of the comparison between the different Codes, the original equations for the variation of wind speed with terrain category and height above ground have been converted and split into two parts (Table 7.3). So it becomes obvious that there are some small differences in the roughness factor K_R and the roughness coefficient α according to the terrain category (Table 7.4). All Codes follow a “power law” for the wind model, except EN that applies a logarithmic law.

Formulas for effective wind pressure, including the effects of terrain category, drag coefficient and gust factors are given in Clause 7.5.

Combined wind loading factors including the effects of gust, height, and terrain are compared in Table 7.6 for conductors and in Table 7.7 for lattice towers. IEC is the only standard where the impact of height above ground on wind speed is combined with the gust response factor in a combined wind factor.

A comparison of the values of drag coefficient for conductors and lattice towers are given in Clause 8. IEC/CIGRE, EN, ASCE and NESC all specify a value of 1.0 for conductors. ASCE adopts a value of 1.0 to 1.4 for snow-covered conductors. For tower steelwork IEC/CIGRE and EN use the same formula.

A comparison of the span factors adopted in the different codes is given in Clause 9. There are fairly small differences between IEC/CIGRE and EN, but ASCE/NESC varies significantly from the other documents.

Table 10.1 compares the use of adjustment factors on ice weight and thickness depending on conductor height and diameter, and Table 10.2 considers the treatment of unbalanced ice loading in the various documents.

Table 11.1 highlights the differences in drag coefficient on iced conductor and the density of ice adopted for different types of icing.

Clause 12 gives brief notes on the failure containment loads given in the different documents.

Clause 13 notes that all documents contain guidance on construction and maintenance loadings.

Clause 14 mentions that IEC provides statistical methods to achieve strength co-ordination between the least reliable components. ASCE provides appropriate strength levels for relative reliability. There is only general guidance being given in EN and no explicit mention of this subject in NESC.

Clause 15 looks at other loading conditions not mentioned above. It notes the ASCE provides guidance on galloping, vibration, flooding and high intensity winds, especially tornadoes, which are not explicitly mentioned in the other documents. Seismic effects are mentioned by EN, ASCE and NESC. EN also provides guidance on loadings generated by short-circuits and avalanches.

Appendix A gives a comparison between conductor wind pressures, including gust, height and span related effects for a range of conductors for wind spans varying from 200-600 m and mean conductor heights of 10 m, 30 m, and 50 m. Terrain category B to IEC or the closest equivalents to the other codes is assumed. This information is given in tabular form in Tables A.1-A.3, and in graphical form in Figures A.1-A.3. It is shown that IEC/CIGRE and EN agree fairly closely, but ASCE gives significantly lower values than either of the other documents. The main reason for this is believed to be the use of the simplified Davenport gust response model. It may be noted that the use of the full Davenport model is allowed as an option in ASCE, and this gives results much closer to IEC.

Table A.4 provides a comparison of conductor wind loadings calculated in accordance with the EN-NNA documents for various European countries, with IEC/CIGRE, ASCE, and the EN Main Body. The countries concerned are Norway, Sweden, Finland, Czech Republic, and the UK. This information is also provided in graphical form in Fig A.4. It appears that the Norwegian, Swedish, Finnish, and UK NNAs give values similar to ASCE, whilst the Czech NNA follows EN.

17. CONCLUSION OF SECTION III

The main issue of this Section III was to compare the recently published International Standard IEC 60826 Ed.3 on “Design Criteria of Overhead Transmission Lines”, issued October 2003 with the existing Codes EN 50341-1, ASCE 74 and NESC 2002, and to assess the consistency. These Codes followed the Reliability Based Design method developed in the IEC Technical Report 826 issued in 1991, a previous version of IEC 60826. CIGRE WG B2.06 already contributed to the review of this Technical Report in the Technical Brochure 109 and with the Companion Document Technical Brochure 178. The detection of the most significant differences between IEC 60826 and the other Codes is a new step in the improvement of RBD Codes.

This Section III concludes with the comparison of results of the numerical calculations of conductor wind loadings between the different codes, including the National Normative Annexes of EN 50341-3.

APPENDIX A - COMPARISON OF WIND PRESSURES FOR DIFFERENT CODES

Calculations carried out by Chris Thorn and Pekka Riisiö

Tables A.1 to A.4

Effective wind pressures, taking account of gust, span and height effects have been calculated in Tables A.1 to A.3 for wind span lengths between 200 m to 600 m:

Table A.1 for mean conductor height 10 m;
Table A.2 for mean conductor height 30 m;
Table A.3 for mean conductor height 50 m;
Figure A.1 for mean conductor height 10 m;
Figure A.2 for mean conductor height 30 m;
Figure A.3 for mean conductor height 50 m.

Table A.4 provides a comparison between conductor wind loadings, calculated in accordance with the EN-NNA documents for various European countries, with IEC/CIGRE, ASCE, and the EN Main Body:

Table A.4 for mean conductor height 30 m and span length 400 m;
Figure A.4 for mean conductor height 30 m and span length 400 m.

General Assumptions

Wind Speed: 24 m/s (10 minute mean wind speed)
Conductor diameter: 30 mm
Air temperature: 15 °C

Notes: Terrain Categories are not entirely compatible between the different codes, but the closest equivalent has been chosen.

Table A.1 - Effective wind pressures on conductors for terrain category B to IEC assuming a reference wind speed of 24 m/s 10 minute average period and mean height of conductor = 10 m

Code	Terrain Category	Average Time	Adjusted wind speed (m/s)	Drag factor	Air density (kg/m^3)	Combined Factors for given span length					Effective Wind Pressures (N/m^2) for given span length				
						200m	300m	400m	500m	600m	200m	300m	400m	500m	600m
IEC	B	10 min	24.0	1.0	1.225	1.85	1.798	1.743	1.691	1.648	653	634	615	597	582
CIGRE	B	10 min	24.0	1.0	1.225	1.85	1.798	1.743	1.691	1.648	653	634	615	597	582
EN	II	10 min	24.0	1.0	1.225	1.771	1.703	1.654	1.617	1.586	625	601	584	570	560
ASCE	C	3 sec	34.3	1.0	1.226	0.738	0.703	0.679	0.662	0.639	532	507	490	478	461
NESC	C	3 sec	34.3	1.0	1.226	0.738	0.703	0.679	0.662	0.639	532	507	490	478	461

Notes:

1) The terrain categories quoted are considered to be the nearest equivalents from the various codes.
2) The ASCE and NESC adjusted wind speed values have been obtained by multiplying the 24 m/s 10 min mean wind speed by 1.43 to convert to 3 sec gust wind speed, as recommended in ASCE 74 Appendix E.
3) The combined factors and effective wind pressures include the effects of gust, conductor height and span length.

Table A.2 - Effective wind pressures on conductors for terrain category B to IEC assuming a reference wind speed of 24 m/s 10 minute average period and mean height of conductor = 30 m

Code	Terrain Category	Average Time	Adjusted wind speed (m/s)	Drag factor	Air density (kg/m^3)	Combined factors for given span length					Effective wind pressures (N/m^2) for given span length				
						200m	300m	400m	500m	600m	200m	300m	400m	500m	600m
IEC	B	10 min	24.0	1.0	1.225	2.23	2.168	2.101	2.038	1.987	787	765	741	719	701
CIGRE	B	10 min	24.0	1.0	1.225	2.23	2.168	2.101	2.038	1.987	787	765	741	719	701
EN	II	10 min	24.0	1.0	1.225	2.321	2.232	2.169	2.120	2.080	819	788	765	748	734
ASCE	C	3 sec	34.3	1.0	1.226	0.884	0.847	0.821	0.803	0.789	638	610	592	579	569
ANSI	C	3 sec	34.3	1.0	1.226	0.884	0.847	0.821	0.803	0.789	638	610	592	579	569

Notes:

1) The terrain categories quoted are considered to be the nearest equivalents from the various codes.
2) The ASCE and NESC adjusted wind speed values have been obtained by multiplying the 24 m/s 10 min mean wind speed by 1.43 to convert to 3 sec gust wind speed, as recommended in ASCE 74 Appendix E.
3) The combined factors and effective wind pressures include the effects of gust, conductor height and span length

Table A.3 – Effective wind pressures on conductors for terrain category B to IEC assuming a reference wind speed of 24m/s 10 minute average period and mean height of conductor = 50 m

Code	Terrain Category	Average Time	Adjusted wind speed (m/s)	Drag factor	Air density (kg/m^3)	Combined Factors for given span length					Effective wind pressures (N/m^2) for given span length				
						200m	300m	400m	500m	600m	200m	300m	400m	500m	600m
IEC	B	10 min	24.0	1.0	1.225	2.43	2.362	2.289	2.221	2.165	857	833	808	784	764
CIGRE	B	10 min	24.0	1.0	1.225	2.43	2.362	2.289	2.221	2.165	857	833	808	784	764
EN	II	10 min	24.0	1.0	1.225	2.60	2.50	2.43	2.38	2.33	918	883	858	839	823
ASCE	C	3 sec	34.3	1.0	1.226	0.96	0.92	0.90	0.88	0.86	695	667	648	634	624
ANSI	C	3 sec	34.3	1.0	1.226	1.01	0.97	0.94	0.90	0.90	727	697	676	646	646

Notes:

1) The terrain categories quoted are considered to be the nearest equivalents from the various codes.
2) The ASCE and NESC adjusted wind speed values have been obtained by multiplying the 24 m/s 10 min mean wind speed by 1.43 to convert to 3 sec gust wind speed, as recommended in ASCE 74 Appendix E.
3) The combined factors and effective wind pressures include the effects of gust, conductor height and span length

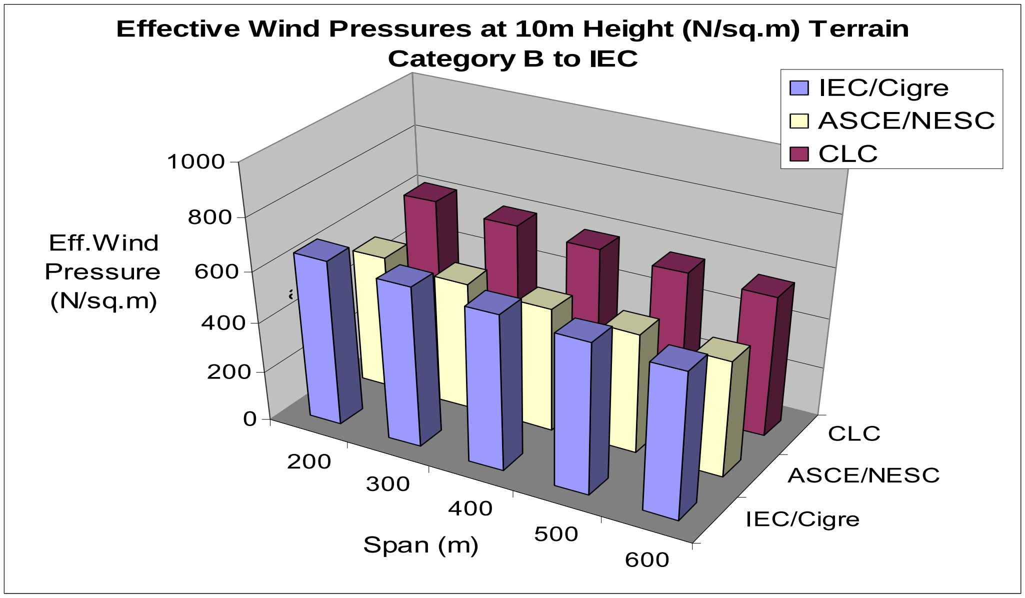

Fig A.1 - Comparison of Effective Wind Pressure on conductors for EN (CLC), ASCE/NESC, and IEC/CIGRE for various span lengths and a height of 10 m above ground for Terrain Category B to IEC or equivalent.

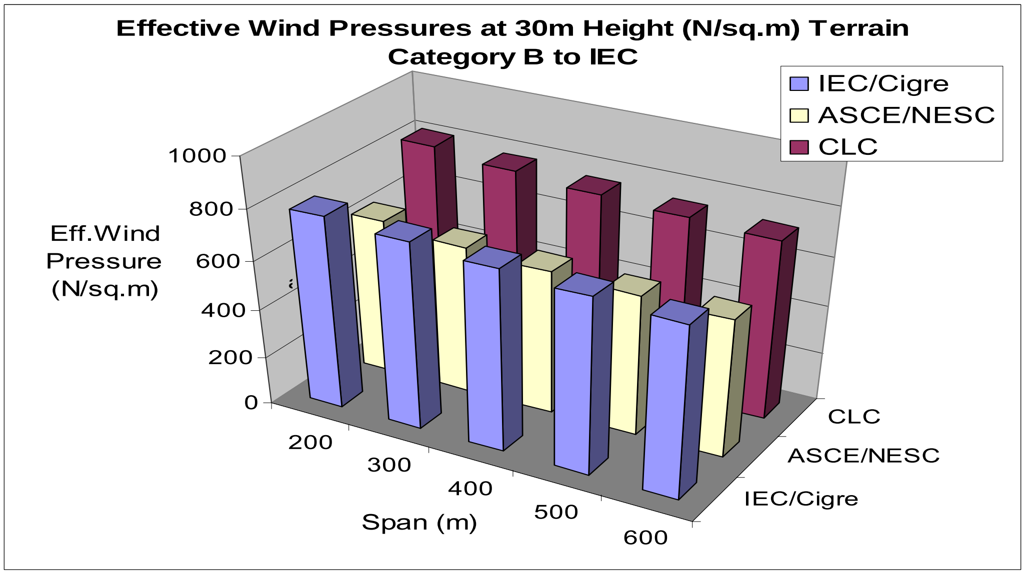

Fig A.2 - Comparison of Effective Wind Pressure on conductors for EN (CLC), ASCE/NESC, and IEC/CIGRE for various span lengths and a height of 30 m above ground for Terrain Category B to IEC or equivalent.

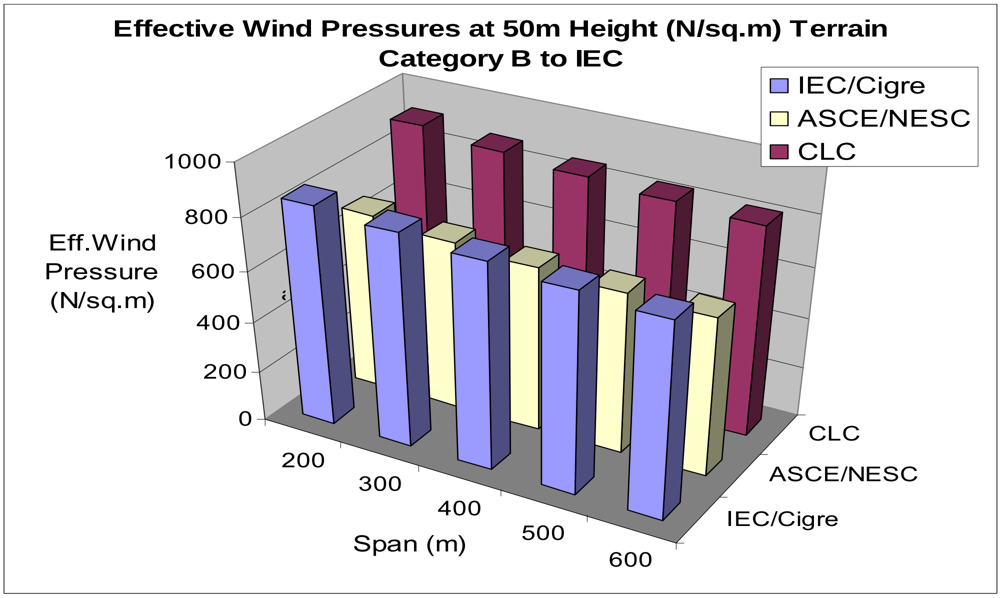

Fig A.3 - Comparison of Effective Wind Pressure on conductors for EN (CLC), ASCE/NESC, and IEC/CIGRE for various span lengths and a height of 50 m above ground for Terrain Category B to IEC or equivalent.

Table A.4 (begin)

Effective wind pressures on conductors under extreme wind loadings having been calculated in accordance with IEC, EN, ASCE/NESC and the EN-NNAs of Finland, Sweden, Norway and the UK

Comparison of Conductor Wind Loads derived from different Standards

Pekka J Riisio & Chris Thorn			
BASIC DATA	Symbol	Unit	Value
Reliability level			1
Return period of loads	T	years	50
Conductor diameter	d	mm	30
Conductor height (average)	h	m	30
Span length	L	m	400
Terrain category			II
Altitude (from sea level)	H_0	m	0
Air temperature	T_a	°C	15
Reference wind speed (terrain II)	V_R(II)	m/s	24.0

Table A.4 (End)
Effective wind pressures on conductors under extreme wind loadings having been calculated in accordance with IEC, EN, ASCE/NESC and the EN-NNAs of Finland, Sweden, Norway and the UK

			IEC	ASCE NESC	EN	EN - NNA			
LOAD PARAMETERS (EN)	**Symbol (EN)**	**Unit**	60826	74	MB	FI	SE	NO	UK
Terrain category			B	C	II	II	II	II	II
Terrain factor	k_T	-	K_R=1.00		0.19	0.19		0.19	
Ground roughness parameter	z_0	-			0.05	0.05		0.05	
Reference wind speed at site	V_R	m/s	24.0	34.3	24.2	24.2		24.0	21.4
Span factor	G_{Xc}	-	G_L=0.94		0.81	0.65	0.50	0.70	0.51
Height correction factor	K_h	-		K_Z=1.26	1.21	1.21		1.21	1.20
Gust factor for wind speed	k_g	-			1.36	1.36		1.36	1.06
Gust factor for wind pressure	$G_q = k_g^2$	-		G_w=0.65	1.84	1.84		1.84	
Combined wind factor for L=200 m	G_C	-	2.23						
Combined wind factor (See § 7.4)	G	-	2.10	1.03	2.17	1.74		1.88	2.21
Mean wind speed at conductor height	$V_h = K_h . V_R$	m/s			29.2	29.2		29.0	
Gust wind speed at conductor height	$k_g . V_h$	m/s			39.6	39.6		39.3	
Altitude factor for density		-	1.00		1.00	1.00		1.00	
Temperature factor for air density		-	1.00		1.00	1.00		1.00	
Air density	ρ or μ	kg/m^3	1.225	1.226	1.23	1.23		1.23	1.22
Gust pressure at conductor height	$(\mu.V_h^2/2).G_q$	N/m^2	788		959	959	920	946	
Drag factor	C_{Xc}	-	1.00	1.00	1.00	1.00	1.00	1.00	
Load factor for wind load (or Speed)	γ_w	-	1.00	1.00	1.00	1.00	1.30	1.00	1.00
Design wind pressure	Q_d	N/m^2	788		959	959	1196	946	
Wind load of conductor per unit length	$Q_c = Q_d.G_{Xc}.d$	N/m	22.3		23.3	18.6	17.9	19.9	
Effective wind load on wind span	$F_c = Q_c.L$	N	8911		9305	7444	7176	7948	
Effective wind pressure on conductor	$Q_d.G_{Xc}$	N/m^2	743	593	775	620	598	662	615

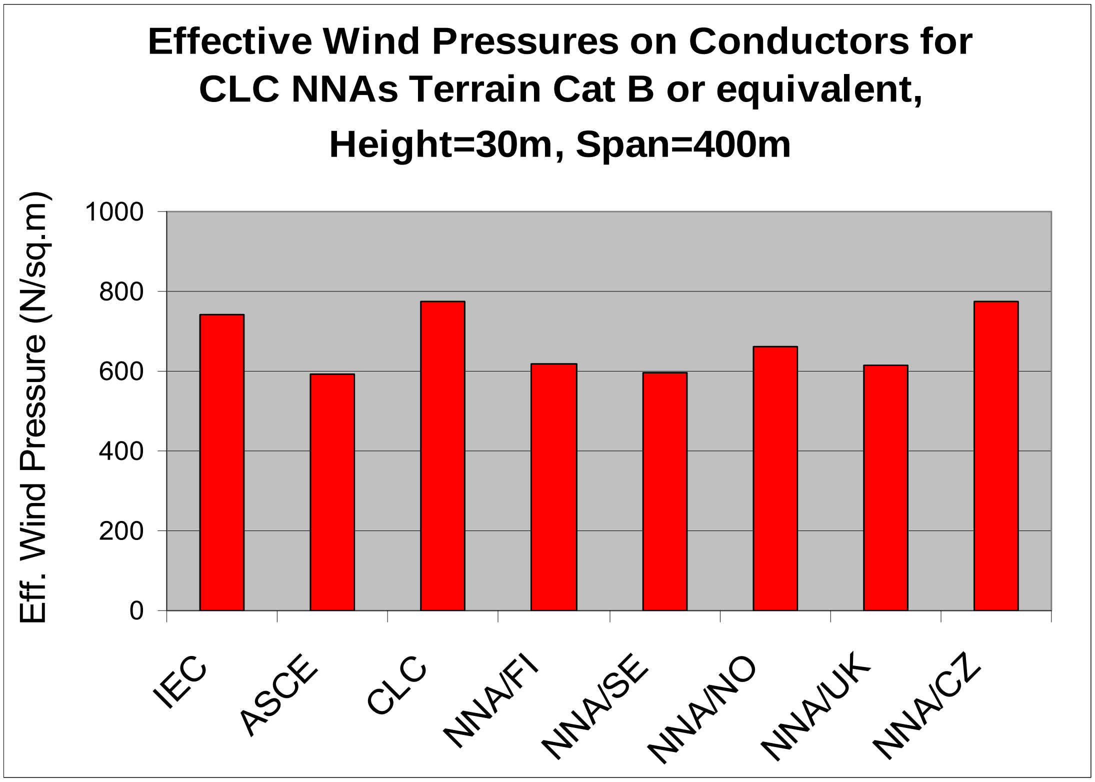

Fig A.4 - Effective wind pressures on conductors for CLC NNAs Terrain Category B or equivalent, height = 30 m, span = 400 m.