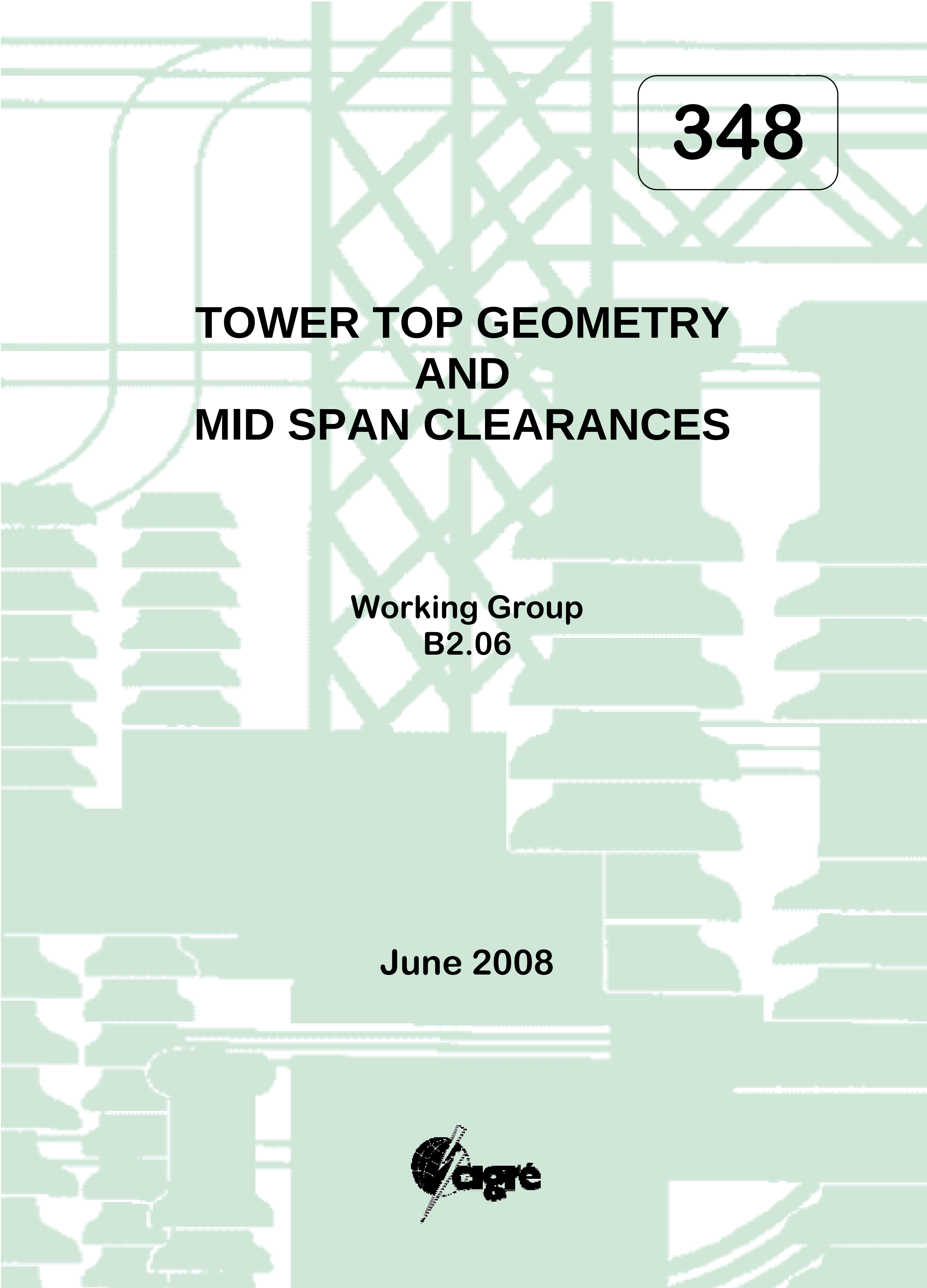

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TOWER TOP GEOMETRY AND MID SPAN CLEARANCES

Working Group
B2.06

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WG B2.06

Tower Top Geometry and Mid Span Clearances

June 2008

Contributors

Convenor: Pavel Fronek (Czek Republic)
Members: Koji Fukami; Friedrich Kiessling; Jan Rogier
Jan ROGIER, WG Convenor (Belgium); Pavel FRONEK, Secretary (Czech Republic)Regular members**:**
Hee-sung AHN (Korea); Jarlath DOYLE (Ireland); Koji FUKAMI (Japan); Angel GALLEGO (Spain); Elias GHANNOUM (Canada); Jean-François GOFFINET (Belgium), Tip GOODWIN (USA); Robert LAKE (New Zealand); Xi-Dong LIANG (China); Ghyslaine McCLURE (Canada); Vivendhra NAIDOO (South Africa); Carlos do NASCIMENTO (Brazil); Krzysztof PUT (Poland); Fabien RANCOULE (France); Oswaldo REGIS (Brazil); Lars ROLFSENG (Norway); Erik RUGGERI (USA); Ljiljana SAMARDZIC (Serbia); Sava SKROBONJA (Serbia); Chris THORN (United Kingdom)

Corresponding members:
Svein FIKKE (Norway); Arturo GAJARDO (Chile); Asim HALDAR (Canada); Trevor JACOBS (Australia); Farid KHADRI (Algeria); Friedrich KIESSLING (Germany); Pierre MARAIS (South Africa); Väino MILT (Estonia); Dzevad MUFTIC (South Africa); João Felix NOLASCO (Brazil); Pekka RIISIÖ (Finland); Sergey TURBIN (Ukraine); Brian WAREING (United Kingdom); George WATT (Canada)

Reviewers: Dale DOUGLASS (USA); José Henrique Machado FERNANDES (Brazil)

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List of symbols

Symbol	**Unit**	**Signification**	**Eq.**
A_{ins}	m^2	Insulator set area exposed to wind	2.14
b	m	Outside diameter of conductor bundle	1.1
C_{xc}	-	Drag coefficient of conductor	2.1
C_{xins}	-	Drag coefficient of insulator set	2.14
c_{min}	m	Minimum clearance between conductors	1.1
D_{pe}	m	Minimum phase-to-earth clearance (Table 3.1)	-
D_{pe_ff}	m	Phase-to-earth clearance for fast front overvoltages	3.1
D_{pe_pf}	m	Phase-to-earth clearance for power frequency voltages	3.10 3.13
D_{pe_sf}	m	Phase-to-earth clearance for slow front overvoltages	3.2
D_{pp}	m	Minimum phase-to-phase clearance (Table 3.1)	-
D_{pp_ff}	m	Phase-to-phase clearance for fast front overvoltages	3.4
D_{pp_pf}	m	Phase-to-phase clearance for power frequency voltages	3.12 3.14
D_{pp_sf}	m	Phase-to-phase clearance for slow front overvoltages	3.5
d	m	Diameter of conductor	2.1
d_S	m	Horizontal deviation of conductor	1.9
F_{WC}	N	Wind load on conductor	2.10
F_{Wins}	N	Wind load on insulator set	2.1
f	m	Sag of conductor	1.1
G_C	-	Gust factor of conductor depending on terrain category and height above ground	2.10
G_L	-	Span factor according to span length	2.10
g	m/s^2	Gravitational acceleration	2.14
H	m	Altitude	3.3
h	m	Min clearance between conductors in a horizontal plane	1.10
h_c	m	Horizontal component of minimum clearance c_{min}	1.10
K	-	Coefficient of empirical equation for mid span clearances	1.1
k_C	-	Factor of empirical equation for mid span clearances	1.1
k_L	-	Span coefficient according to span length	2.12
k_T	-	Terrain factor	2.9
k_W	-	Parameter for Figure 2.5	2.18
k_a	-	Altitude factor	3.3
k_{cs}	-	Statistical coordination factor	3.7
k_g	-	Gap factor	3.1
k_{g_pf}	-	Gap factor for power frequency	3.11
k_{z_ff}	-	Deviation factor for fast front withstand voltage	3.6
k_{z_pf}	-	Deviation factor for power frequency voltage	3.13
k_{z_sf}	-	Deviation factor for slow front withstand voltage	3.7
k_α	-	Factor taking account of the envisaged exclusion limit	3.10
k_1	-	Reduction factor for clearance for fast and slow front overvoltages (Table 1.2)	-
L_W	m	Wind span of conductor	2.1

L_C	m	Weight span of conductor	2.14
L_0	m	Minimum horizontal distance between tower structure and first conductor attachment point	5.4
L_1	m	Minimum horizontal distance between adjacent conductor attachment points	5.5
l_{ins}	m	Mean length of suspension insulator set	1.1
M_{ins}	kg	Mass of insulator set	2.14
m	-	Exponent for altitude factor k_a	3.3
m_C	kg/m	Linear mass of conductor	2.14
n	-	Number of sub-conductors	2.1
P	-	Probability	2.2
q_z	N/m^2	Mean wind pressure corresponding to the mean wind velocity V_z at height z above ground	2.10
T	years	Return period of climatic event	2.3
U	kV	Voltage	1.2
U_R	kV	Nominal voltage	1.2
U_S	kV	Highest system voltage	1.2
U_{max_sf}	kV	Max. slow front (switching impulse) overvoltage	3.2
U_0	-	Constant coefficient, mostly $U_0 = 150$	1.3
$U_{50\%\_ff}$	kV	Fast front (lightning impulse) overvoltage being withstood with 50% probability	3.1
$U_{90\%\_ff}$	kV	Fast front (lightning impulse) overvoltage being withstood with 90% probability	3.6
V	m/s	Wind velocity	2.2
$\overline{V}$	m/s	Mean value of yearly maximum wind velocities	2.2
V_R	m/s	Reference mean wind velocity for reference height z_R	2.8
V_T	m/s	Wind velocity with return period T	2.3
V_z	m/s	Mean wind velocity at height z above ground	2.8
V_{obs}	m/s	Observed yearly maximum wind velocity	2.2
V_p	m/s	Recorded peak gust wind velocity	2.1
V_η	m/s	Parameter for Weibull distribution	2.4
v	m	Min clearance between conductors in a vertical plane	1.10
v_c	m	Vertical component of minimum clearance c_{min}	1.10
W_C	N	Conductor weight	2.1
W_{ins}	N	Weight of insulator set	2.1
z	m	Height above ground	2.8
z_R	m	Reference height above ground	2.8
z_0	m	Roughness length	2.9
α	-	Roughness exponent depending on the terrain category	2.8
β	-	Parameter for Weibull distribution	2.4
ρ	kg/m^3	Air density	2.1
σ_V	m/s	Standard deviation of yearly maximum wind velocities	2.2
$\sigma_ø$	°	Standard deviation of the swing angle	2.16
ø	°	Swing angle	2.1
$ø_C$	°	Swing angle of conductor	2.15
$ø_{ins}$	°	Swing angle of insulator set	2.14

General Introduction

The geometry of the tower top must be designed to ensure that the internal electric clearances necessary between live parts and supporting earthed structures as well as between conductors within the span, especially in mid span, are achieved.

The available clearances depend on the conductor and insulator positions which vary due to the action of wind. Therefore, wind action plays an important role when defining tower top geometries.

In CIGRE Technical Brochure No. 48 “Tower Top Geometry” the internal clearances between live conductors and earthed structures under the action of wind were considered. The present Technical Brochure gives, in addition, guidance on the calculation of internal clearances between conductors within the span under the influence of differential wind velocity.

For structural design conventional approaches based on “working loads” for climatic actions combined with “factors of safety” were replaced by new methods based on Reliability Based Design (RBD) considerations. There, a wind velocity having a given return period is selected as the basis for structural design representing an ultimate load which may stress the structure to its ultimate strength capacity.

For the design of the tower top geometry the same meteorological data should be used to determine the positions of conductors and insulator sets. The required clearances should be derived from the electrical characteristics of the transmission system. The approach presented in this Technical Brochure for the design of the tower top geometry complies with these aims and represents an improvement on the various empirical methods in use for this purpose.

In CIGRE Technical Brochure No. 48 it was agreed that under “still air” conditions, which were taken to include small and frequently occurring swing angles, the gap should be wide enough to withstand the anticipated lightning and switching impulses. The probability of flashover is then given by the probability of the gap not withstanding the lightning or switching surges which can be considered as rare events.

As extreme wind loads causing maximum swing angles are rare events, the probability of the simultaneous coincidence with a lightning or switching surge will, therefore, be some orders of magnitude smaller than under “still air” conditions. Hence, it is unrealistic to combine extreme swing angles with clearances designed for lightning or switching surges. However, under extreme wind conditions the clearance must be sufficient to withstand power frequency voltages.

These considerations lead to several questions which had to be answered by the Working Group 06 of CIGRE SC B2:

- Which extreme wind conditions have to be combined with the various electrical stresses?
- Would it be necessary to apply the ultimate wind loads adopted for structural design?
- Would there be a real concern that a flashover might occur under a load that stresses the structure close to its failure limit?

As was done with the study of clearance between live parts of insulator sets and earthed structures in Technical Brochure No. 48, the task is split into several parts:

- Part 1 reviews the existing practices on internal clearances, for which information was gathered by a questionnaire and completed with information from Standards;
- Part 2 deals with the determination of swing angles of conductors and insulators under wind load. It is assumed that wind load is randomly distributed and can be described by statistical parameters;
- Part 3 studies available information on electrical clearances required for the various conditions;
- Part 4 gives proposals for the coordination of conductor positions and electrical clearances;
- Part 5 demonstrates the approach developed by means of an example.

The design guidance is limited to the influence of wind loads on the conductor position, but the approach can be extended to other issues such as:

- Differential sags caused by differential ice loading;
- Ice loading combined with reduced wind loading. It may be appropriate to consider that ice as well as wind loading will vary between conductors;
- Ice drop;
- Galloping;
- Live line maintenance techniques, including differential sags between phases caused by the presence of conductor trolleys, etc.

No design guidance is provided for those issues, but they are considered in Part 1.

The study resulted in the proposal to consider two cases when designing the tower top geometry and mid span clearances in view of conductor and insulator swing under the action of wind load:

- In “still air” or under moderate winds there should be adequate clearance to withstand the lightning or switching surge impulse voltages with a probability of more than 90%. Still air conditions apply to conductor positions occurring during at least 99% of the operation period.

- Under “high wind” the clearances should be adequate to withstand the power frequency voltage only. The probability of flashovers depends on the probability of occurrence of the corresponding wind velocity. For a wind velocity having a return period of 50 years the probability of flashover will be 1% per year at maximum.

Tower Top Geometry
and
Mid Span Clearances

Executive Summary

Introduction

The aim of the Technical Brochure is to give guidance on the calculation of the geometric dimensions of tower top to ensure that the internal electrical clearances necessary between live parts and earthed structures as well as between conductors in mid span are achieved.

The available clearances depend on the conductor and insulator set positions which vary due to wind action. The wind speed causes swinging of conductors and reduces their clearances. Therefore, wind loads are significant for defining the tower top geometry.

CIGRE Technical Brochure No. 48 on “Tower Top Geometry” [1], issued in 1996, already provided guidelines to check the internal clearances at towers. The present Technical Brochure reviews those guidelines and extends them to the clearances between conductors within the span.

As the design of mid span clearances is more complex due to the additional influence of conductor sag, and possible asynchronous oscillation of adjacent conductors due to differential wind speed, a questionnaire has been issued by CIGRE WG B2.06 to collect and compare existing national design methods.

The probabilistic approach developed in the Technical Brochure represents an improvement on the various empirical methods in use up to now.

- Part 1 analyses the existing practices on internal clearances, for which information was gathered by the questionnaire and completed with information from European Standards, including the empirical equations;

- Part 2 deals with the determination of swing angles of conductors and insulator sets under wind load. It is assumed that wind speed is randomly distributed. Especially “still air” and “high wind” conditions are considered;

- Part 3 compares available information on electrical clearances phase-to-earth and phase-to-phase required for the various conditions of lightning or switching surge impulse and power frequency voltages;

- Part 4 gives proposals for the coordination of conductor positions and electrical clearances;

- Part 5 demonstrates the approach developed by means of an application example.

The study presented is valid for all self-supporting and guyed overhead line supports and for all line configurations (vertical, horizontal, triangle).

The design guidance is limited to the influence of wind actions, but the approach philosophy can easily be extended to other issues such as:

- Differential conductor sags caused by differential ice accretion;
- Combined ice and wind loading;
- Ice drop;
- Galloping;
- Live line maintenance.

No design guidance is provided for those issues, but they are considered in Part 1.

Part 1: Existing national practices

In most countries existing practices for the definition of tower top geometry refer to National Standards or Codes, which quote appropriate formulae and meteorological conditions (temperature, wind, ice) to determine swing angles of:

- insulator sets at tower top;
- conductor at mid span,

to associate them with corresponding internal electrical clearances:

- The phase-to-earth clearance refers to the internal clearance between phase conductors and objects at earth potential, including the tower structure and the earth wire;
- The phase-to-phase clearance refers to the internal clearance between phase conductors.

Part 1 of the Technical Brochure reviews the information referring to the different aspects of loading cases considered for the determination of internal clearances.

The information received from the answers to the questionnaire was completed with the design rules for clearances available in the National Normative Aspects (NNAs) EN 50341-3 to the European Standard EN 50341-1 [2]. Since the publication of the Technical Brochure No. 48, national practices have been changed in some countries.

The following countries responded to the WG B2.06 questionnaire:

Australia, Belgium, Brazil, Czech Republic, Finland, France, Germany, Great Britain, Italy, Japan, Lithuania, the Netherlands, New Zealand, Norway, Serbia, South Africa, Ukraine and USA.

The practices of the following countries have also been considered, as they are detailed in the NNAs of EN 50341-3:

Austria, Denmark, Estonia, Greece, Iceland, Ireland, Portugal, Spain and Sweden.

The European Standard EN 50341-1 distinguishes three load cases for the internal clearances. They are summarized in **Table1.** Clearance type 1 is required to withstand lightning (fast front) or switching (slow front) impulse voltages. Clearance type 3 is required to withstand power frequency voltages. Clearance type 2 is an intermediate case with a reduction factor applied to clearance type 1.

Table 1 – Type of internal clearance per load case (EN 50341-1)

Type	Electrical stress of the air gap	Load case
1	Lightning / switching impulse voltage	Still air conditions with maximum conductor temperature or ice load
2	Reduced impulse voltage	Reduced wind load (T = 3 years)
3	Power frequency voltage	Extreme wind load (T = 50 years)

All information gathered from the questionnaire and the NNAs of EN 50341 has been summarized in the Technical Brochure in various synoptic tables. All wind and/or ice load cases are classified per country with the corresponding type of clearance.

According to the answers to the questionnaire the most used load cases correspond to the recommendations of EN 50341-1. They have been ranked in **Table 2** with the preferred clearance type according to Table 1.

Table 2 – Ranking of load cases for the internal clearances

Ranking		Load case	Preferred clearance type (Table 1)
No.	%		
1	76%	Maximum temperature	1
2	68%	High wind load	3
3	64%	Reduced wind load	2
4	60%	Extreme ice load	1

Galloping is mentioned by 32% of the countries as a determining factor for mid span clearances. Other load cases are applied by only 24% or less of the countries. Some countries consider different wind or ice loads on adjacent conductors.

Many countries use an empirical equation for the mid span clearance between adjacent conductors if they are made of the same material and having the same cross-section and sag. This equation includes three terms:

- The first term indirectly takes into account the differing wind speeds on the conductors. This term depends on the sag, the mean length of the suspension insulator set, the swing angle and the relative position of both conductors;
- The second term takes into account the system voltage;
- Finally the third term considers the outside diameter of conductor bundles, if any.

A synoptic table in the Technical Brochure summarizes per country the parameters used for the empirical equation.

Part 2: Swing angles

Part 2 of the Technical Brochure compiles the material on swinging of conductors due to wind loads, which is available to the WG B2.06. The wind action varies with time and space and can be described as randomly distributed using statistical approaches [1; 2; 3; 4].

Due to the boundary effect, the wind velocities increase with the height above ground. The longer the wind span the more the wind velocity will vary along this span. Relevant standards, take care of this effect by introducing a span factor. Additionally, the swing angles depend on line parameters such as ratio of wind span to weight span, conductor type, etc.

For the design of the tower top geometry the same meteorological data should be used as for the Reliability Based Design (RBD) [3; 4] methods.

Various experimental investigations were carried out on test stands in the past to study the relation between wind velocities and swing angles. The basic results are:

- The swing angle observed for a measured wind velocity, whether instantaneous or average over a certain period of time, scatter considerably;

- The majority of observed swing angles stay well below those determined theoretically using observed peak wind velocities and generally agreed formulae.

To determine the distribution of swing angles it is necessary to establish the time distribution of wind velocities.

For large wind velocities having a return period of more than two years the Gumbel distribution can be adopted, which is based on the measured annual maximum wind velocities.

For relatively small wind velocities the most appropriate approach to establish a time distribution would be to evaluate the wind statistics from weather stations over the year. Alternatively, this time distribution can be established based on a Weibull distribution, the parameters of which can be derived from wind velocities having a probability of occurrence of 1 or 2 years.

Often wind statistics refer only to the occurrence of maximum wind values without referring to wind directions. However, only winds acting perpendicularly to the span will cause the maximum swing angle. In order to take care of the variation of wind intensity with its direction the time probability of the swing angles can be assumed as being half of the corresponding wind velocities when the swing angle is more than 2°.

Part 3: Required clearances

The required clearances should be derived from the electrical characteristics of the transmission system. There are various approaches available to determine the clearances necessary to withstand given electrical stresses.

According to IEC 60071-1 the standard highest system voltages for equipment are divided into two ranges:

- Range I: above 1 kV to 245 kV included;
- Range II: above 245 kV.

For lines within range I lightning (fast front) impulses decide on the insulation level and for lines within range II switching (slow front) impulses.

The standards IEC 60071-1 [5] and IEC 60071-2 [6] deal only with phase-to-earth clearances and impulse voltages. The Cigre Technical Brochure No. 72 [7] deals with the dielectric strength of external insulation and conductors, lightning and switching impulses.

The Technical Brochure lists the clearances under impulse and power frequency voltages according to the IEC, CIGRE and EN. The various formulae are also given in detail in the Technical Brochure.

Part 4: Coordination of conductor positions and electrical stresses

The study resulted in a proposal to consider at least two cases when designing tower top geometry and mid span clearances, taken into account the varying position of conductors and insulator sets under the wind action and the electrical stress of the air gap by power frequency voltage and overvoltages caused by lightning strokes or switching operations (**Table 3**).

- Case 1 is described by conductor and insulator positions which would occur under the action of the design wind velocities having a return period T of say 50 years. These positions are combined with clearances required to withstand power frequency voltage. The probability of flashovers depends on the probability of occurrence of the corresponding design wind velocity. For a wind velocity having a return period of 50 years the probability of flashover will be 1% per year at maximum.

- Case 2 is described by conductor and insulator positions which are assumed as not being exceeded during 99% of the time. These positions are combined with clearances required to withstand the lightning or switching overvoltages with a probability of more than 90%. The flashover probability is that by which the design overvoltage conditions will be exceeded.

Table 3 – Coordination of conductor positions and electrical stresses

Electrical stress of the air gap		Conductor and insulator positions	
		Still air or moderate wind during 99% of time	High wind velocity with T = 50 years
	Probability	High	Low
Power frequency voltage	High	Covered by Cases 1 & 2	Case 1
Lightning / switching impulse voltage	Low	Case 2	Not considered

Part 5: Application example

The approach proposed to determine tower top geometry and mid span clearances is demonstrated by means of an example for a suspension tower equipped with a twin conductor bundle ACSR 564/72. The mean value of the yearly maximum wind velocities is 20 m/s (10 min mean value, height 10 m), the coefficient of variation is 14%. The highest system voltage is 420 kV and the switching impulse voltage is 1050 kV. The mean suspension insulator length is 5,0 m, the sag 20 m and the distance between sub-conductors 0,4 m.

The design of the tower top is performed in 5 steps. The detailed calculation is given in the Technical Brochure.

- The wind velocity with a return period of 50 years is calculated according to the Gumbel distribution function for extreme values. The moderate wind velocity is calculated using the Weibull distribution function;

- The wind velocities are adjusted to the time period of measurement and the height above ground according to the IEC 60826 equations. In **Tables 4 and 5** the results are given for a 5 minute mean wind speed 20 m above ground level;

- The results for the swing angle of the suspension insulator set at tower and the swing angle of conductors at mid span are somewhat different;

- Further the scattering of the swing angle is determined:

  - The maximum swing angle at tower is obtained by adding two standard deviations to the mean swing angle of the insulator (Table 4);
  - For the adjacent conductors both the minimum and maximum swing angles are obtained respectively by deducing and adding two standard deviations (Table 5);

- Finally the minimum electrical clearances taken from IEC and CIGRE are used to determine the horizontal distance between:
    - The attachment point of the first conductor and the tower structure (5,0 m);
    - The attachment points of two adjacent conductors in a horizontal configuration (6,7 m).

The numerical results of the calculations are summarized in Table 4 and depictured in **Figure 1** for the clearances between insulator set and earthed structure at tower and in Table 5 and **Figure 2** for clearances between adjacent conductors in mid span. The Technical Brochure also compares these results for other alternatives.

Table 4 – Clearances between insulator set and earthed structure

Wind			**Insulator swing angle**			
Pos.	Wind condition	Wind speed 5 min, 20 m	Mean swing angle	Standard deviation	Max. swing angle	Distance cond. to earth
			ø	σ_{ϕ}	ø+2σ_{ϕ}	
		m/s	°	°	°	m
1	*T* = 50 years	32,0	42,2	2,2	46,6	4,99
2	Swing 1% of year	16,1	12,9	1,5	15,9	4,97

Table 5 – Clearances between adjacent conductors in mid span

Wind			**Conductor swing angle**				
Pos.	Wind condition	Wind speed 5 min, 20 m	Mean swing angle	Standard deviation	Swing angle		Dist. cond. to cond.
					min	max	
			ø	σ_{ϕ}	ø -2σ_{ϕ}	ø+2σ_{ϕ}	
		m/s	°	°	°	°	m
1	*T* = 50 years	32,0	43,7	2,2	39,3	48,1	-
2	Swing 1% of year	16,1	13,5	1,5	10,5	16,5	6,70

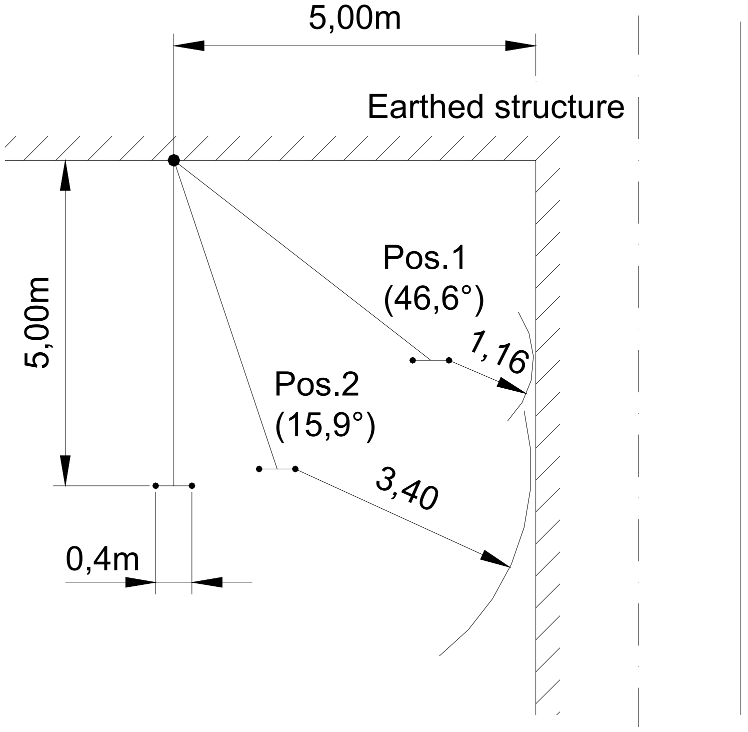

Figure 1 – Example of clearances between insulator set and earthed structure

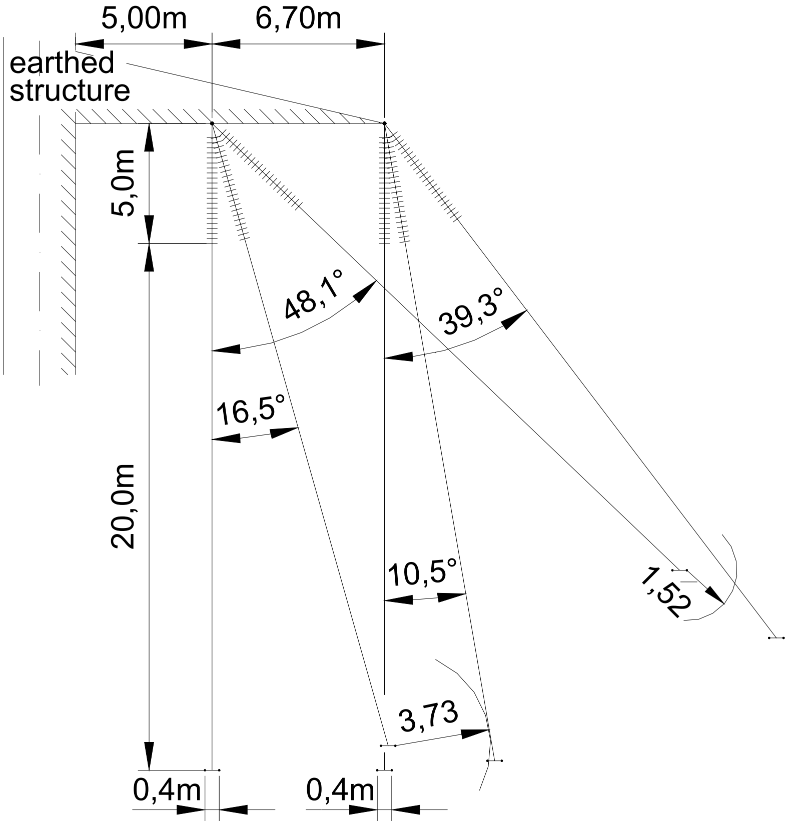

Figure 2 – Example of clearances between adjacent conductors in mid span

Conclusion

The present Technical Brochure aims to calculate the geometric dimensions of tower top to ensure that the internal electrical clearances necessary between live parts and earthed structures as well as between conductors in mid span are achieved.

In comparison with CIGRE Technical Brochure No. 48 on “Tower Top Geometry”, the method developed has been extended to the clearances between conductors within the span. The probabilistic approach represents a significant improvement of the various empirical methods in use up to now. On the basis of the review of national practices, the study results in a proposal to consider two cases when designing:

- the tower top geometry;
- the mid span clearances,

in view of conductor and insulator swing under wind action and the electrical stress of the air gap.

The approach proposed to determine tower top geometry and mid span clearances is demonstrated by means of an example for a suspension tower equipped with a twin conductor bundle ACSR 564/72.

Reference wind speeds, ice loads, electrical stresses as well as parameters, such as the number of standard deviations to consider, have to be selected accordingly on the basis of experience and specific studies.

References

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Part 1: Existing practices to define internal clearances at tower and at mid span

1.1 Introduction

In most countries existing practices for definition of tower top geometry refer to National Standards or Codes, which quote appropriate formulae and meteorological conditions (temperature, wind, ice) to determine conductor sags and swing angles at mid span and insulator swing angles at tower top to associate them with corresponding internal electrical clearances.

Most of the standards and codes of practice stipulate different internal clearances at tower top depending on the wind loading cases. They consider reduced probability of voltage surges and high wind loads occurring simultaneously. Therefore, the study distinguishes the different “swung conditions” from the “still air conditions”.

This Part 1reviews the existing information referring to the different aspects of loading conditions considered for the determination of internal clearances. Therefore a questionnaire has been issued by WG B2.06 to collect all information available regarding mid span clearances.

This information has been completed with the design rules for internal clearances at tower and at mid span that are incorporated in the National Normative Aspects (NNAs) to the European Standard EN 50341-1 [8]. Since the publication of the Technical Brochure 48 on “Tower Top Geometry” [4], the practices for the definition of the internal clearances at tower have been changed in many European countries.

Therefore this Part 1 includes not only the present practices for the definition of mid span clearances, but also for the clearances between the conductor and the earthed tower structure.

This study is valid for all self-supporting and guyed supports of overhead lines and all line configurations (vertical, horizontal, triangle). Nevertheless, for the simplicity the word “tower” has been used instead of “support” throughout the Technical Brochure.

1.2 Internal clearances at tower and at mid span

1.2.1 Geometry

The geometry of the upper part of the tower depends on:

- The configuration of the conductors in the circuit systems;
- The minimum internal clearances.

The configuration of the conductors in the circuit system can be:

- Vertical;
- Horizontal;
- Angular (delta, triangular, etc.).

For the internal clearances, distinction has been made between:

- Clearance between phase conductors;
- Clearance between the phase conductor and the earth wire or the earthed parts of the tower.

The internal clearances are checked:

- At the tower;
- In the span, especially at mid span.

1.2.2 At tower

At the tower, the position of the suspension insulator set (or the jumper of the tension tower) changes with the wind load on both the conductor and the insulator set (or on the jumper). Therefore, for the check of the internal clearance between the conductor and the earthed parts of the tower such as the tower structure, the cross-arms (the horizontal member and the oblique member) and possibly the climbing system, the swing angle of the insulator set is considered mainly for two extreme insulator set positions:

- “Still wind conditions” without any wind load, or with a moderate wind load;
- “Swung angle conditions”, mainly for a high wind speed (e.g. with a return period of 50 years).

Some countries also consider intermediate swing angles for a wind speed with a 3 year return period if a high wind speed with a 50 year return period is considered.

1.2.3 At mid span

In order to prevent clashing and flashover between conductors in mid span, the conductors shall be attached to the support at a proper distance from each other.

According to the results of the questionnaire, the determination of the clearances between the conductors at mid span is more complex than at the tower.

The conductor sag at mid span changes mainly with:

- the conductor temperature;
- the ice load.

1.2.4 Differential wind load

Moreover, due to long experience and statistical results there is a need to consider different wind loads on adjacent conductors in a horizontal configuration. Therefore many countries use relatively simple empirical equations to avoid long calculations. Those formulae are summarized in Table 1.8.

The internal clearances determined by the experimental equations depend on the:

- Relative position of the conductors (and earth wire) considered;
- Conductor sag at mid span (including the mean vertical length of the suspension insulator sets).

1.2.5 Differential ice load

In the same way differential ice accretion is considered for conductors in a vertical configuration, except if the horizontal offset is sufficient. There are also some typical equations available for this approach.

1.2.6 Summary

Finally, the tower top geometry depends on:

- The vertical clearance between conductors, that is mainly determined by the “still wind conditions” at tower, except if galloping and possibly if a differential ice load is considered;
- The horizontal length of the cross-arms to the first conductor, that is mainly determined by the “swung conditions” at tower;
- The horizontal clearance between conductors, that is mainly determined by the differential “swung condition” at mid span.

Most practices are based on those principles. Some countries consider various load cases to determine the tower geometry. Those load cases are summarized in Table 1.6. The values of the corresponding internal clearances are given in Table 1.5.

1.3 Questionnaire

The questionnaire on Mid Span Clearances is given in Appendix B. The answers are summarized in Tables A.1 and A.2 of Appendix A.

The following countries responded to the questionnaire:

Australia (AU), Belgium (BE), Brazil (BR), Czech Republic (CZ), Finland (FI), France (FR), Germany (DE), Great Britain (GB), Italy (IT), Japan (JP), Lithuania (LT), the

Netherlands (NL), New Zealand (NZ), Norway (NO), Serbia (RS), South Africa (ZA), Ukraine (UA) and USA (US).

The practices of the following countries have also been considered, as they are detailed in the National Normative Aspects to the European Standard EN 50341-1 (See Clause 1.4):

Austria (AT), Denmark (DK), Estonia (EE), Greece (GR), Iceland (IS), Ireland (IE), Portugal (PT), Spain (ES) and Sweden (SE).

The following results can be drawn from the answers to the questionnaire summarized in Tables A.1 and A.2 of Appendix A.

- Question 1 – Almost in all countries (94%) the mid span clearances are specified in national standards, regulations or laws. 53% of the countries have additional design methods.
- Question 2 – In most countries (77%) mid span clearances are determined by empirical equations summarised in Table 1.8. Only 35% use direct clearance values. Only Japan (6%) uses a probabilistic method. Japan, Norway and South Africa (18%) use other methods too.
- Question 3 – Japan is the only country that applies probabilistic principles for mid span clearances. Germany and South Africa declare to use simplified probabilistic methods to define load cases for mid span clearances. All other countries have deterministic approaches.
- Question 4 – In 59% of the standards the withstand voltages are directly determined. Only in 18% of the cases they are based on probabilistic methods and determined by statistical distribution of overvoltages.
- Question 5 – 71% of the responders provided the list of their voltage systems and the overvoltages as well. They are summarized in Table 1.4.
- Question 6 – The mechanical reliability levels to ensure the mechanical performance of the lines are not at all relevant for the determination of mid span clearances.
- Question 7 – The electrical reliability levels are only in 12% of the cases relevant for the determination of the mid span clearances.
- Question 8 – 71% of the responders provided the list of the load cases and the corresponding minimum clearances. They are summarized in Tables 1.5 and 1.6.
- Question 9 – There is no country where the load cases for determination of mid span clearances and load cases for components strength are identical.
- Question 10 – 32% of the countries considers galloping for the determination of mid span clearances.
- Question 11 – In 35% of the countries effects of ice dropping are considered.
- Question 12 – 6% of the responders consider dynamic forces caused by short-circuit currents for the mid span clearances. Only the effect on spacers in bundle conductors is considered.
- Question 13 – 82% of the responders considers the same clearances between conductors of different circuits.
- Question 14 – In 29% of the countries the mid span clearances are increased to take into account live line maintenance.

1.4 European practice for internal clearances

Since the publication of the European Standard EN 50341-1 [8], some European countries have updated their design rules for the internal clearances according to the European approach. The National Normative Aspects (NNAs) in the Standard EN 50341-3 reflect the current national practice in each European country affiliated to CENELEC.

Therefore it is useful to summarize the European approach detailed in EN 50341-1.

1.4.1 Required clearances according to EN 50341-1

There are two types of internal clearances considered in EN 50341-1:

- D_{pe} and D_{pp} – Minimum air clearance required to prevent a disruptive discharge during fast front (lightning impulse) or slow front (switching impulse) overvoltage;
- D_{pe_pf} and D_{pp_pf} – Minimum air clearance to prevent a disruptive discharge at power frequency.

Phase-to-earth clearances D_{pe} and D_{pe_pf} refer to the internal clearances between phase conductors and objects at earth potential, including the tower structure and the earth wire.

Phase-to-phase clearances D_{pp} and D_{pp_pf} refer to the internal clearances between phase conductors.

The internal clearances according to EN 50341-1 are summarized in **Table 1.1**.

Table 1.1 – Internal clearances according to the European Standard EN 50341-1

Voltage level		Clearance for fast & slow front overvoltages		Clearance for power frequency voltage	
Nominal voltage	**Highest system voltage**	**Conductor - earth wire or tower**	**Conductor - conductor**	**Conductor - earth wire or tower**	**Conductor - conductor**
U_R	U_S	D_{pe}	D_{pp}	D_{pe_pf}	D_{pp_pf}
kV	**kV**	**m**	**m**	**m**	**m**
45	52	0,60	0,70	0,11	0,17
66	72,5	0,70	0,80	0,15	0,23
110	123	1,00	1,15	0,23	0,37
132	145	1,20	1,40	0,27	0,42
150	170	1,30	1,50	0,31	0,49
220	245	1,70	2,20	0,43	0,69
380	420	2,80	3,20	0,70	1,17
480	525	3,50	4,00	0,86	1,47

The values for D_{pe} and D_{pp} given in Table 1.1 are based on the analysis of commonly used European values.

Fast front overvoltages of importance for overhead lines are mainly lightning overvoltages due to direct strokes to the phase conductors or back-flashovers or, in the lower system voltage range (≤ 245 kV), voltages induced by lightning strokes to earth close to the line. Slow front overvoltages can originate from faults, switching operations or distant direct lightning strokes to overhead lines.

The electrical clearances D_{pe_pf} and D_{pp_pf} to withstand power frequency voltage given in Table 1.1 are valid only for internal clearances to be used in extreme wind conditions. They result from the numerical application of the formulae in Annex E of EN 50341-1 for D_{pe_pf} with a gap factor k_g = 1,45 and D_{pp_pf} with a gap factor k_g = 1,6. Those formulae are presented in clause 3.2.3 of this Technical Brochure.

The electric system is usually designed by a nominal system voltage U_R. The system voltage is the rms phase-to-phase power frequency voltage of the electric system. The representative continuous power frequency voltage is considered as constant and equal to the highest system voltage U_S, the highest value of operating voltage which occurs under normal operating conditions at any time and any point in the system. Temporary overvoltages are oscillatory overvoltages at power frequency at a given location, of relatively long duration, and which are undamped or weakly damped.

1.4.2 Loading cases according to EN 50341-1

For internal clearances, such as those caused by the swing of the conductors due to wind loading, it is permitted – in contradiction with external clearances – to use lower values than D_{pe} and D_{pp} , because they affect only the electrical reliability of the network. There is only a low probability that there will be an overvoltage under these conditions and the occurrence of a flashover would not result in danger to persons or properties. Therefore, the internal clearances $k_1 \cdot D_{pe}$ and $k_1 \cdot D_{pp}$ are defined in the NNAs of EN 50341-3, where $k_1 < 1$.

The following shall be applied when considering internal clearances (**Table 1.2**):

- Under still air conditions - especially based on the maximum continuous service temperature of the conductor or on the maximum ice accretion - internal clearances are greater than or equal to D_{pe} or D_{pp} (called clearance type 1);

- Under extreme wind conditions (i.e. 50 year return period) internal clearances D_{pe_pf} and D_{pp_pf} shall withstand the highest system voltage phase-to-earth in directly-earthed neutral systems with earth fault factor of 1,3 and below (called clearance type 3);

- At the design wind load for determination of electrical clearances (i.e. 3 year return period) internal clearances D_{pe} and D_{pp} may be reduced by a reduction factor k_1, that is defined in the NNAs of EN 50341-3 (called clearance type 2).

Simultaneous occurrence of a transient overvoltage and a climatic event with a long return period is considered to be acceptably small.

The correspondence between the loading cases and the minimum internal clearances within the span and at the tower are summarized in Table 1.2.

Table 1.2 – Loading cases for internal clearances according to the European Standard EN 50341-1

Type of internal clearance	**Internal clearance**		**Load case**
	Conductor - earth wire or tower	**Conductor - conductor**	
1	D_{pe}	D_{pp}	Still air conditions - Maximum conductor temperature - Characteristic ice load
2	$k_1 \cdot D_{pe}$	$k_1 \cdot D_{pp}$	Reduced wind load (e.g. T = 3 years) (for k_1, see all NNAs in EN 50341-3)
3	D_{pe_pf}	D_{pp_pf}	Extreme wind load (e.g. T = 50 years)

Higher values for minimum clearances are given in the NNAs or in Project Specifications. These values will overrule those in the Standard and its Annexes. The clearances are checked according to load conditions of each country.

The reference wind speed and the characteristic ice load to be applied are specified directly based on the experience and/or statistical data of each country.

When calculating serviceability limits, such as clearances, the partial load factors shall not be applied.

Guidance for the calculation of the shielding failure flashover rates and the back-flashover rates are not considered in this Technical Brochure.

1.5 Summary of the practices of the countries

In the following Tables 1.4 to 1.8 practices are summarised per country.

1.5.1 Levels of overvoltages

Table 1.4 provides the list of overvoltages per country, as provided by the responders to the questionnaire. The following characteristics are given if available:

- Nominal system voltage (kV);
- Highest system voltage (kV);
- Lightning impulse (fast front overvoltage) (kV);
- Switching impulse (slow front overvoltage) (kV);
- Temporary power frequency overvoltage (kV).

1.5.2 Internal clearances

Table 1.5 summarizes per country the internal clearances classified per type of clearance (1, 2 or 3) according to Table 1.2 above, where:

U_R	Nominal system voltage level;
U_S	Highest system voltage level;
D_{pe} and D_{pp}	Clearance type 1 (for fast and slow front overvoltages);
$k_1 \cdot D_{pe}$ and $k_1 \cdot D_{pp}$	Clearance type 2 (with reduction factor k_1);
D_{pe_pf} and D_{pp_pf}	Clearance type 3 (for power frequency voltages).

For some countries (Belgium, Greece, Italy) a fourth clearance type (2*) has been defined.

The values of the clearances according to EN 50342-1 are repeated in Table 1.5. The internal clearances in Denmark, Estonia, Germany, Norway and Portugal are completely in accordance with those EN values.

The value of the reduction factor k_1 for clearance type 2 is given in Table 1.5 under the name of the country. It varies from k_1 = 0,60 (for Czech Republic and Norway) to k_1 = 1,0 (for the Netherlands). The mean value for 9 countries (Czech Republic, Denmark, Estonia, Finland, Germany, Iceland, the Netherlands, Norway and Portugal) is 0,73.

1.5.3 Loading cases for internal clearances

Table 1.6 summarizes per country the loading cases considered and their corresponding type of clearance (1, 2 or 3).

In the questionnaire various loading cases have been identified. They are numbered from 1 to 13. Empirical equations are characterized by “E”. For other loading cases described by the responders to the questionnaire, numbers 21, 22 and 23 have been allocated:

E: Empirical equation for the clearance between conductors or between a conductor and an earth wire;
1. Maximum conductor temperature, no wind, no ice;
2. Minimum conductor temperature, no wind, no ice;
3. Other conductor temperature, no wind, no ice;
4. Low wind speed, no ice;
5. Reduced wind speed, no ice;
6. Extreme wind speed; no ice;
7. No wind, characteristic or extreme ice load;
8. Extreme wind speed, reduced ice load;
9. Reduced wind speed, characteristic or extreme ice load;
10. No wind, different ice load on upper and lower conductor;
11. No wind, different (or unbalanced) ice load on adjacent spans;
12. Different wind speed on adjacent conductors, no ice;
13. Different wind speed on adjacent conductors, extreme ice load;

21. Galloping (for combined wind and ice load);
22. Reduced wind speed, different ice load on upper and lower conductor;
23. Minimum temperature, reduced wind speed, no ice load.

Table 1.6 provides for each load case the following values in the last 8 columns:

- Temperature (°C);
- Wind intensity characterized by:
  - Mean wind speed (m/s);
  - Wind pressure (N/m^2);
  - Return period of wind speed (years)
- Return period of ice load (years);
- In case of difference between either wind or ice loads on adjacent conductors, the reduction for the lowest load is expressed in % of the highest load (100% means that the lowest load is zero);
- Indication with “P” if an alternative is allowed in the Project Specification;
- Type of clearance referring to Table 1.5. If “P” is indicated, reference is made to the Project Specification. If “N” is indicated, reference is made to the National Normative Aspects (NNA) of EN 50341-3. If “E” is indicated, reference is made to Table 1.8 for the empirical equations.

1.5.4 Coordination of loading cases and their type of clearance

Table 1.7 summarizes per country and per loading case the type of clearance (1, 2 or 3 according to Table 1.2). If “P” is indicated, reference is made to the Project Specification. If “X” is indicated, the type of clearance is unknown.

At the end of the table the loading cases are ranked according to the total number of applications.

It seems that the most used load cases correspond to the clearance type recommendations of EN 50341-1 Standard in Table 1.2 above:

1. 76% - Load case 1 – Maximum temperature – 72% for clearance type 1;
2. 68% - Load case 6 – High wind load – 52% for clearance type 3;
3. 64% - Load case 5 – Reduced wind load – 60% for clearance type 2;
4. 60% - Load case 7 – Extreme ice load – 44% for clearance type 1.

Galloping is mentioned by 32% of the countries as a determining factor for mid span clearances. The other load cases are applied by only 24% or less of the countries.

Some countries consider different wind or ice loads on adjacent conductors. Nevertheless the empirical equation can take into account different loadings on adjacent conductors.

68% of the countries use an empirical equation. It will be discussed in the following clause 1.5.5.

1.5.5 Empirical equations for mid span clearances

Table 1.8 summarizes the parameters used by various countries when an empirical equation is considered for the mid span clearance:

- Between adjacent conductors or;
- Between a conductor and an earth wire.

Clearances between conductors within a span are determined on the basis of the deviation image. This check is made to determine the convergence of neighbouring conductors under different loading conditions assuming equidirectional deviation by wind load. Similarly the convergence of conductors when the lower conductor bounces back after drop of additional loads may be checked, both in the deviated and in the non-deviated state of the conductor.

One of the most known empirical approaches is the German method described in the German NNA or EN 50341-3-4 [9]. For the purpose of this study this approach has been considered as a reference in order to comment on the differences with other national equations.

When applying an approximate approach extensive computer aided calculations of the swinging of phases relatively to each other or to the earth wires will be avoided.

It is generally permitted to use the empirical formula if conductors are made of the same material, having the same cross-section and the same mid span sag. If this method is used, the minimum clearance $c_{\min}$ of the conductors measured at mid span in still air (i.e. without any lateral deviation) is at least:

$$c_{\min} = k_{C} \sqrt{f + l_{\text{ins}}} + K \cdot D + b \quad \text{(expressed in m),} \tag{1.1}$$

where:

f	sag of the conductor in the middle of the span generally for the loading conditions producing the greater value (m);
l_{ins}	mean length of the suspension insulator set swinging orthogonal to the line direction (m);
k_{C}	factor which depends on the swing angle or angle of deviation $ø$ of both conductors and on their (horizontal, diagonal or vertical) arrangement (e.g. derived from Table 1.3 as applicable for Germany [9] and Austria and Belgium as well) (-);
K	constant coefficient which depends on the experience of the country (-);
D	minimum clearance D_{pe} for phase-to-earth clearances and D_{pp} for phase-to-phase clearances (m);
b	outside diameter of the conductor bundle for phase-to-phase clearances (m) (or half the outside diameter if a phase bundle to earth clearance is considered, or b = 0 for single conductors).

For the second term in (1.1) there are two alternatives:

- In the German formula the second term $K{\cdot}D$ is proportional to the internal clearance specified by the European Standard EN 50341-1 (coefficient K is not identical to reduction factor k_1 from Table 1.2);
- For some countries the second term is replaced with $K{\cdot}U$ or U/U_0. Then the term is proportional to the nominal voltage U_R or to the highest system voltage U_S.

For the last alternatives, empirical equation (1.1) becomes:

$$c_{\min} = k_C \sqrt{f + l_{\text{ins}}} + K \cdot U + b \quad \text{(expressed in m)}, \qquad (1.2)$$

or

$$c_{\min} = k_C \sqrt{f + l_{\text{ins}}} + U / U_0 + b \quad \text{(expressed in m)}, \qquad (1.3)$$

where:

K	constant coefficient which depends on the experience of the country (-);
U	nominal voltage U_R or the highest system voltage U_S (expressed in kV);
U_0	constant coefficient, mostly $U_0 = 150$.

The first term of equations (1.1), (1.2) and (1.3) takes indirectly into account the differing wind speeds on the adjacent conductors. It depends on the total sag f, the mean length of the suspension insulator set l_{ins} , the swing angle $ø$ and the relative position of both conductors. The second term takes into account the voltage level of the system. Finally the third term takes into account the outside diameter b of conductor bundle, if any.

Only three countries (Austria, Belgium and Germany) apply the German values for the determination of factor k_C (in the first term) in function of the swing angle $ø$ and the relative position of the conductors. Those values are summarized in **Table 1.3**.

Table 1.3 – Coefficient k_C for the approximate equation [9]

Range of swing angle	**Angle between vertical and plane through conductors**		
	~ horizontal	**triangular**	**~ vertical**
ø	**90° to 80°**	**80° to 30°**	**30° to 0°**
> 65°	0,70	0,75	0,95
55° to 65°	0,65	0,70	0,85
40° to 55°	0,62	0,65	0,75
< 40°	0,60	0,62	0,70

The swing angle $ø$ is obtained from the ratio of the wind load acting on the conductor and the dead weight of the conductor.

Some countries provide a value for k_C which does not change with the relative position of both conductors. So it is not clear whether they are also valid for an angular of a vertical configuration of the conductors. In the Czech Republic, Italy and Portugal factor k_C only depends on the conductor type. Only one country (Denmark) does not provide any term for the asynchronous movement of adjacent conductors. They seem to refer to Project Specifications.

In case of calculation of clearances under wind load condition, generally the effect of wind load on the reduction of conductor temperature is neglected for the calculation of sag f in the first term of (1.1).

Austria, the Czech Republic, Sweden and Ukraine also consider ice loading for the determination of sag f if this case produces a greater value.

If circuits with differing operational voltages run in parallel on the same structures, then the most unfavourable value for D_{pe}, D_{pp} or U is used.

In the case of conductors with different cross sections, materials or sags the higher factor k_C and the higher sag f are used for determining the internal clearances.

If the conditions are not fulfilled for using approximate formula, guidance is given for differing wind speed on adjacent conductors.

For the vertical distance between conductors in case of (differing) ice accretion, reference is made to the next Clause 1.6.

Japan is the only country that applies probabilistic principles for mid span clearances. They are very similar to the approach presented in Parts 2, 4 and 5 (See Clause 1.6.16).

The protection angle of the shield wire with respect to the phase conductors complying with the allowable number of flashovers per line length and per year due to a direct lightning stroke into the phase conductors, is not considered in this study.

Table 1.4 – Levels of overvoltages

Country	Nominal voltage	Highest system voltage	Lightning impulse (fast front overvoltage)	Switching impulse (slow front overvoltage)	Temporary power frequency overvoltage
	kV	kV	kV	kV	kV
Belgium	70	82,5	380		
	150	170	750		
	220	245	1050		
	380	420	1425		
Brazil	138	145	550-650	-	205
	230	245	1050-1150	700	346
	345	362	1300-1425	750	512
	500	525	1600-1800	1050	742
	750	800	3100	1500	1131
Czech Republic	110	123	550	-	230
	220	245	1050	-	460
	380	420	1425	1050	-
Finland	110	123	450	-	230
	220	245	750	-	360
	400	420	1300	1050	-
Germany	110	123	450-550	-	
	220	245	850-1050	-	
	380	420	1050-1425	850-1050	
Great Britain	66	72,5	325	-	
	132	145	550	650	
	275	300	1050	850	
	400	420	1425	1050	
Japan		240	-	970	-
		300	-	1213	-
		525	-	1472	-
		550	-	1541	-
Lithuania		123	550	312	
		362	1050	800	
Netherlands	66	72,5			
	110	123			
	150	170			
	220	245	850	750	360
	380	420	1425	1050	-
New Zealand		110	450	550	
		220	850	950	
		275	950	1050	
		330	1050	1175	
		500	1300	1550	
Norway		52	325		

		145	650		
		300			
Portugal	66	72.5	325-400	250	
	150	170	550-750	550	
	220	245	850-1050	650-850	
	380	420	1175-1425	950-1425	
Serbia	110	123	450-550	-	-
	220	245	650-1050	-	-
	400	420	1050-1425	950-1050	-
South Africa		145	550	-	230
		245	850	-	360
		300	1050	1300	-
		420	1425	1550	-
		800	2100	2400	-
Sweden		52	250	-	95
		72,5	325	-	140
		145	550	350	230
		170	650	425	275
		245	850	650	360
		420	1175	950	-

Table 1.5 – Internal clearances

Clearance type			**1**		**2***	**2**		**3**	
Country	U_R	U_S	D_pe	D_pp	$k_1'\cdot D_\mathrm{pe}$	$k_1\cdot D_\mathrm{pe}$	$k_1\cdot D_\mathrm{pp}$	$D_\mathrm{pf\_pe}$	$D_\mathrm{pf\_pp}$
	kV	**kV**	**m**	**m**	**m**	**m**	**m**	**m**	**m**
EN 50341 (Tables 5.1, 5.4 and 5.5)	45	52	0,60	0,70				0,11	0,17
	66	72,5	0,70	0,80				0,15	0,23
	110	123	1,00	1,15				0,23	0,37
	132	145	1,20	1,40				0,27	0,42
	150	170	1,30	1,50				0,31	0,49
	220	245	1,70	2,00				0,43	0,69
	275	300	2,10	2,40				0,51	0,83
	380	420	2,80	3,20				0,70	1,17
	480	525	3,50	4,00				0,86	1,47
Austria			E	2)		E	Z		
	110	123	0,88	1,15		0,73	0,73		
	150	170	1,20	1,62		1,00	1,00		
	220	245	1,76	2,30		1,50	1,50		
	380	420	2,50	3,05		2,50	2,50		
Belgium	70	82,5	0,85		0,74	0,47		0,22	0,38
	150	170	1,66		1,46	1,00		0,46	0,79
	220	245	2,34		2,06	1,47		0,67	1,16
	380	420	3,18		2,79	2,54		1,17	2,02
Brazil	138	145	1,13	1,95		0,91	1,17	0,27	0,42
	230	245	1,75	3,03		1,05	1,69	0,43	0,69
	345	362	2,38	4,12		1,74	2,78	0,62	1,00
	500	525	3,00	5,20		2,74	4,63	0,92	1,55
Czech Republic (k_1 = 0,60)	110	123	1,00	1,20		0,60	0,72	0,25	0,40
	220	245	1,80	2,20		1,08	1,32	0,45	0,70
	380	420	2,50	3,70		1,50	2,22	0,75	1,20
Denmark (k_1 = 0,70)	110	123	1,00	1,15		0,70	0,81	0,23	0,37
	220	245	1,70	2,20		1,19	1,54	0,43	0,69
	380	420	2,80	3,20		1,96	2,24	0,70	1,17
Estonia (k_1 = 0,75)	110	123	1,00	1,15		0,75	0,86	0,23	0,37
	220	245	1,70	2,20		1,28	1,65	0,43	0,69
	330	362	2,50	2,85		1,88	2,14	0,62	1,02
	380	420	2,80	3,20		2,10	2,40	0,70	1,17
	480	525	3,50	4,00		2,63	3,00	0,86	1,47
Finland (k_1 = 0,65)	110	123	0,90	1,40		0,59	0,91	0,23	0,37
	220	245	1,50	2,30		0,98	1,50	0,43	0,69
	400	420	2,90	3,90		1,89	2,54	0,70	1,17
France	90	100	1,10			0,80		0,15	0,34
	225	245	1,70			1,10		0,40	1,05
	400	420	3,00			2,00		0,70	1,73

Germany (k_1 = 0,75)	110	123	1,00	1,15		0,75	0,86	0,23	0,37
	220	245	1,70	2,20		1,28	1,65	0,43	0,69
	380	420	2,80	3,20		2.10	2,40	0,70	1,17
Great Britain (k_1: see PS)	66	72,5	0,70	0,78					
	132	145	1,10	1,40					
	275	300	2,10	2,40					
	400	420	2,80	3,60					
Greece	150	170	1,30		1,10	0,90		0,50	
	400	420	2,80		2,40	1,20		0,80	
Iceland (k_1 = 0,70)	66	72,5	0,70	0,80		0,49	0,56	0,15	0,23
	132	145	1,20	1,40		0,84	0,98	0,27	0,42
	220	245	1,70	2,20		1,19	1,54	0,43	0,69
Ireland	110	123				0,75			
	220	245				1,00			
	400	420				1,75			
Italy	132	145			0,79			0,25	
	150	170			0,90			0,29	
	225	245			1,35			0,43	
	400	420			2,40			0.76	
Japan		240		2,10				0,54	0,84
		300		2,75				0,68	1,05
		525		3,85				1,18	1,84
		550		4,10				1,23	1,93
Netherlands (k_1 = 1,00)	66	72,5						0,25	0,25
	110	123						0,40	0,40
	150	170						0,55	0,55
	220	245						0,85	0,85
	380	420						1,55	1,55
New Zealand		110		2,00					
		220		2,50					
		275							
		330							
		500							
Norway ($k_1 \geq$ 0,60)		52	0,60	0,70				0,11	0,17
		145	1,20	1,40				0,27	0,42
		300	2,10	2,40				0,51	0,83
		420	2,80	3,20				0,70	1,17
Portugal (k_1 = 0,85)	66	72,5	0,70	0,80		0,60	0,68	0,16	0,20
	150	170	1,30	1,50		1,11	1,28	0,40	0,50
	220	245	1,70	2,20		1,45	1,87	0,60	0,75
	380	420	2,80	3,20		2,38	2,72	1,12	1,41
Serbia	110	123	0,90	0,90					
	220	245	1,75	1,75					
	400	420	2,80	2,80					
Spain	110	123	0,83				0,73		
	150	170	1,10				1,00		
	220	245	1,57				1,47		

	380	420	2,63				2,53		
	480	525	3,30				3,20		
Sweden		52							
		72,5							
		145				1,00	1,15	0,60	0,69
		170	1,40	1,61		1,20	1,38	0,65	0,75
		245	1,85	2,13		1,60	1,84	0,90	1,04
		420	2,60	3,00		2,20	2,53	1,20	1,38

Table 1.6 – Load cases for internal clearances

Country	Loading case	Temperature	Wind intensity	Ice load	Temperature	Mean wind speed	Wind Pressure	Return period wind	Return period ice	Reduction	Altern in Proj. Spec.	Clearance type
					°C	m/s	Pa	y	y	%	P	-
Questi-onnaire	E	Empirical equation										
	1	max	-	-								
	2	min	-	-								
	3	other	-	-								
	4	-	low	-								
	5	-	red	-								
	6	-	ext	-								
	7	-	-	ext								
	8	-	ext	red								
	9	-	red	ext								
	10	-	-	diff								
	11	-	-	unb								
	12	-	diff	-								
	13	-	diff	ext								
	21	-	-	gal								
	22	-	red	diff								
	23	min	red	-								
EN 50341-1 (Table 5.4.3)	E	-	-	-								N
	1	max	-	-	max							1
	5	-	red	-				3				2
	6	-	ext	-				50				3
	7	-	-	ext					-			1
Austria	E	max	-	-	40/60							2
	E	-	-	ext	-5				-			2
	1	max	-	-	40/60							1
	2	min	-	-	-20							1
	6	-	ext	-		33,3						2
	7	-	-	ext	-5				-			1
Belgium	E	-	-	-	40	23						3
	1	max	-	-	75	0						1
	5	-	low	-		11,5						*
	6	-	red	-	40	35						2
	21	-	-	gal								3
Brazil	1	max	-	-	75	1,0						1
	3	other	-	-	15/20							1
	5	-	red	-	10			-				2
	6	-	ext	-	10			50				3

Czech Republic	E	max	-	-	40							2
	E	-	-	ext	-5				-			2
	1	max	-	-	40							1
	2	min	-	-	-30						P	2
	3	other	-	-	10							-
	4	-	low	-	-5/30	10						1
	5	-	red	-	-5/30	75%	58%	3			P	2
	6	-	ext	-	-5/30	24/26	100%	50			P	3
	7	-	-	ext	-5				20			1
	9	-	red	ext	-5	12/13	25%		20		P	2
	10	-	-	diff	-5				3	100		P
	11	-	-	unb	-5				3	100		P
	12	-	diff	-	-5/30	75%	58%	3		36	P	2
	13	-	diff	ext	-5	12/13	25%		20	36	P	2
Denmark	E	-	-	-	0							3
	1	max	-	-	-							1
	5	-	red	-			45°					2
	21	-	-	gal								3
Estonia	1	max	-	-	60							1
	5	-	red	-	15			3				2
	6	-	ext	-	15			50				3
	7	-	-	ext	-5				-			1
	21	-	-	gal							P	P
Finland	E	-	-	-	50			-				E
	1	max	-	-	70							1
	5	-	red	-	0			3				2
	6	-	ext	-	0			50				3
	7	-	-	ext	0				-			1
	10	-	-	diff	0				-	100		1
France	E	-	-	-	15							E
	1	max	-	-	15							1
	5	-	red	-	15		240/360					2
	6	-	ext	-	15		800					3
	7	-	-	ext	-5				-			1
	10	-	-	diff thick	-5				-	75/50		P
Germany	E	-	-	-	40	18/24	464/754	3				2
	1	max	-	-	60/80							1
	5	-	red	-	40			3				2
	7	-	-	ext	-5				3			1
Great Britain	1	max	-	-	P							1
	5	-	red	-	P			3			P	2
	7	-	-	ext	P				3		P	2
	9	-	red	ext	P			-	-		P	P
	10	-	-	diff	P					P		P
	12	-	diff	-	P				-	P		P
Greece	1	max	-	-	50							1
	4	-	low	-			190					*
	5	-	red	-			430					2
	6	-	ext	-			765					3
Iceland	1	max	-	-	P							1
	5	-	red	-				3				2

	6	-	ext	-				50				3
	7	-	-	ext					50			1
	9	-	red	ext				<3	30			3
	11	-	-	unb					50	100		P
	21	-	-	gal								3
Ireland	5	-	red	-			50/52,5°					2
Italy	E	-	-	-	15							E
	1	max	-	-	40/55							1
	4	-	low	-	0	7,2						2
	6	-	ext	-	15	36						3
Japan	4	-	low	-	20	0/20						1
	6	-	ext	-	20	20/40		50				3
	12	-	diff	-	20	8/13				-		3
	21	-	-	gal								3
	22	-	red	diff	-10/0			-	-	-		3
Lithuania	E	max	-	-								E
	E	-	-	ext	-5							E
	1	max	-	-	35							1
	2	min	-	-	-35							1
	3	other	-	-	5							1
	5	-	red	-	-5	12/18	100/200					2
	6	-	ext	-	-5	25/36	200/800					3
	7	-	-	ext	-5				-			1
	21	-	-	gal								P
Nether-lands	E	-	-	-	10							1
	1	max	-	-	70/80	0,6						1
	2	-	red	-				3				1
	6	-	ext	-				50				3
	7	-	-	ext					50			-
	21	-	-	gal								-
New Zealand	E	-	-	-	50		100					E
	10	-	-	diff	0					50		1
Norway	E	-	-	-	50							E
	1	max	-	-	50							1
	4	-	low	-	50		30%					1
	6	-	ext	-	50		100%	50				2
	7	-	-	ext	0				50		P	1
	10	-	red	diff	0			3	3	100		*
	21	-	-	gal								P
Portugal	E	max	-	-	75							1
	5	-	red	-				-				2
	6	-	ext	-				-				3
	7	-	-	ext	-10				-			1
Serbia	E	-	mod	-	40	31/45	600/ 1300	5				1
Spain	E	-	-	-	50		500/600					3
Sweden	E	-	-	ext					-			E
	E	-	-	diff					-	100		E
	E	-	diff	ext				-	-	30		E
	1	max	-	-	50							1
	2	min	-	-	-50/-25							1
	3	other	-	-	15							1

	4	-	low	-	15		150					2
	5	-	red	-	15		500					3
	7	-	-	ext	0				-			3
	9	-	red	ext	0		500		-			3
	23	min	red	-	-30/-5		500					2
Ukraine	E	-	-	-								E
	1	max	-	-	36/40							
	2	min	-	-	-40/-24							
	3	other	-	-	6/12							
	6	-	ext	-	6/12		400/600					
	7	-	-	ext	-10/-5				-			
	9	-	red	ext	-10/-5		150/400		-			

E = Empirical equation
N = specified in National Normative Aspects (NNA) of EN 50341-3 or in Project Specification
P = specified in Project Specification

Table 1.7 – Clearance type per loading case and per country

(1)	Emp Eq.	Load cases of the Questionnaire													Other		
		1	2	3	4	5	6	7	8	9	10	11	12	13	21	22	23
EN	-	1	-	-	-	2	3	1	-	-	-	-	-	-	-	-	-
AT	2	1	1	-	-	-	2	1	-	-	-	-	-	-	-	-	-
BE	3	1	-	-	-	2	2	-	-	-	-	-	-	-	3	-	-
BR	-	1	-	1	-	2	3	-	-	-	-	-	-	-	-	-	-
CZ	2	1	2	X	1	2	3	1	-	2	P	P	2	2	-	-	-
DK	3	1	-	-	-	2	-	-	-	-	-	-	-	-	3	-	-
EE	-	1	-	-	-	2	3	1	-	-	-	-	-	-	P	-	-
ES	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
FI	E	1	-	-	-	2	3	1	-	-	-	1	-	-	-	-	-
FR	E	1	-	-	-	2	3	1	-	-	P	-	-	-	-	-	-
GB	-	1	-	-	-	2	-	2	-	P	P	-	P	-	-	-	-
GE	2	1	-	-	-	2	-	1	-	-	-	-	-	-	-	-	-
GR	-	1	-	-	2	2	3	-	-	-	-	-	-	-	-	-	-
IE	-	-	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-
IS	-	1	-	-	-	2	3	1	-	3	-	P	-	-	3	-	-
IT	E	1	-	-	2	-	3	-	-	-	-	-	-	-	-	-	-
JP	-	-	-	-	1	-	3	-	-	-	-	-	3	-	3	3	-
LT	E	1	1	1	-	2	3	1	-	-	-	-	-	-	P	-	-
NL	1	1	1	-	-	-	3	X	-	-	-	-	-	-	X	-	-
NO	E	1	-	-	1	-	2	1	-	-	2	-	-	-	-	-	-
NZ	E	-	-	-	-	-	-	-	-	-	1	-	-	-	P	-	-
PT	1	-	-	-	-	2	3	1	-	-	-	-	-	-	-	-	-
RS	E	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
SE	E	1	1	1	2	3	-	3	-	3	-	-	-	-	-	-	2
UA	E	X	X	X	-	-	X	X	-	X	-	-	-	-	-	-	-
1	2	18	4	3	3	-	-	11	-	-	1	1	-	-	-	-	-
2	3	-	1	-	3	15	3	1	-	1	1	-	1	1	-	-	1
3	3	-	-	-	-	1	13	1	-	2	-	-	1	-	4	1	-
X	9	1	1	2	-	-	1	2	-	2	3	2	1	-	4	-	-
Tot	17	19	6	5	6	16	17	15	0	5	5	3	3	1	8	1	1
%	68	76	24	20	24	64	68	60	0	20	20	12	12	4	32	4	4

(1) Country Code according to ISO 3166-1

Table 1.8 – Empirical equation to calculate clearances between conductors

$c_{\min} = k_C\sqrt{f + l_{\text{ins}}} + K \cdot D + b$ (measured at "wind still" conditions)

	First term for sags and/or swings: $k_C\sqrt{f + l_{\text{ins}}}$						Second term: $K{\cdot}D_{pe}$, $K{\cdot}D_{pp}$ or U_R/U_0					Minimum
Country	Factor k_C for cond. relative position			Swing angle		Temp sag f	Clearance		Coef K	Clear. case	Differ. load	Abs. min clearance
	horizontal	angular	vertical	ø	T		p-e	p-p				
	~ 90°	~ 60°	~ 0°	°	years	°C	m	m	-	-	%	m
Austria	0,6/0,7	0,62/0,75	0,7/0,95	40°- 65°	33 m/s	40 (1)	-	Z	-	2	-	0,8
Belgium	0,6/0,7	0,62/0,75	0,7/0,95	40°- 65°	35 m/s	40	$K{\cdot}d_m/\sqrt{3}$	$K{\cdot}d_m$	0,75	3	40%	$d_m > 0,2$
Czech Rep.	> 0,54	-	-	cond type	-	40 (2)	$K{\cdot}D_{pe}$	$K{\cdot}D_{pp}$	0,60	2	-	-
Denmark	Particular swing equation			-	-	0	$K{\cdot}D_{pe}$	$K{\cdot}D_{pp}$	0,70	2	-	-
Finland	0,6	~ 0,7	1,0	no	-	50	$K{\cdot}D_{pe}$	$K{\cdot}D_{pe}$	1,00	1	-	-
France	0,6	0,6	0,6	-	-	15	t_1	$t_1{\cdot}\sqrt{3}$	-	-	P	$t_1 = U_R/400$
Germany	0,6/0,7	0,62/0,75	0,7/0,95	40°- 65°	3 y	40	$K{\cdot}D_{pe}$	$K{\cdot}D_{pp}$	0,75	2	40%	K
Italy	0,5/0,6	-	-	cond type	-	15	-	$U_R/100$	-	-	-	-
Lithuania	0,6	-	-	-	-	-	-	$U_R/110+1$	-	-	-	-
Netherlands	0,6	-	-	no	-	10	D_{pp}	D_{pp}	1	1	-	-
New Zealand	≥ 0,4 (3)	-	-	-	-	50	-	$U_R/100$	-	-	-	-
Norway	$V_z/55 > 0,55$	no	no	-	-	50	$U_S/143$	$U_S/143$	-	-	-	-
Portugal	0,6/0,7	same	same	cond type	-	75	D_{pp}	D_{pp}	1	1	-	-
Serbia	Min 0,6	Min 0,7	Min 1,4	cond type	-	40	D_{pp}	D_{pp}	1	1	15%	-
Spain	0,6/0,65/0,7	-	-	45°- 65°	-	50	-	$U_R/150$	-	-	-	$0,1+U/150$
Sweden	0,45	specific	specific	no	-	Ice (4)	$U_S/167$	$U_S/143$	-	-	30% (5)	-
Ukraine(6)	0,6	-	-	-	-	Ice	-	$U_R/110+1$	-	-	-	-

(1) Austria: or -5°C with exceptional ice loading if it produces a greater sag;
(2) Czech Republic: or -5°C with reference ice load (T = 20 years);
(3) New Zealand: k to be increased for extremely turbulent wind conditions and in case of different amount of conductor movement;
(4) Sweden: ice only on upper conductor; (5) Sweden: difference in wind pressure only on dissimilar conductors;
(6) Ukraine: $U_R/150$ +1,0 m for U_R = 500 and 750 kV;
P = Project Specification.

1.6 Specific practices per country

In the Tables 1.4 to 1.8 the practices regarding the determination of the mid span clearances and the load cases are compared and summarized per country.

In this Clause 1.6 specific aspects of mid span clearances are dealt with per country.

1.6.1 Australia

In the design sequence, it is common practice first to calculate electrical clearances at the structure or tower, taking account of access requirements and wind loading, and then to check electrical withstand clearances between phases — first at the structure or tower, and then for mid-span clearances. There are several formulae for calculating phase to phase clearances, some assuming the conductor can swing in an arc.

The following formulae are empirical, based on experience in the country of origin. The formulae all have a term for electrical withstand of air, plus one or two terms for mechanical movement. All formulae have a mechanical movement term based on span, and some also take into account the swing of insulators.

These are commonly used formulae for calculating minimum horizontal mid-span phase to phase clearance.

For calculating minimum horizontal phase separation clearance h, Queensland's practice is to use the following calculation:

$$h = 15\ (d/m_{\mathrm{C}})\ \sqrt{f}\ + 1{,}1\ D_{\mathrm{pe}} \tag{1.4}$$

where:

d = conductor diameter (m);
m_{C} = conductor unit mass (kg/m);
f = sag at every day tension (m);
D_{pe} = impulse clearance to earth (m) (2,4 m for 275 kV).

For calculating minimum vertical phase separation clearance v, Queensland's practice is to use the following calculation:

$$v = 0{,}015\ f\ + 1{,}5\ D_{\mathrm{pe}} \tag{1.5}$$

ESAA Handbook C(b) 1 specifies an other mid-span formula used in Australia for horizontal, vertical and angular clearances c_{min} between conductors:

$$c_{\mathrm{min}} = k_{\mathrm{C}}\ \sqrt{f + l_{ins}}\ + U / U_0 \tag{1.6}$$

where:

k_C = factor = 0,4;
f = greater of the two conductor sags at 50°C (m);
l_{ins} = length of the free swinging insulator string (m);
U = RMS vector difference between conductors (kV);
U_0 = 150 kV.

See New Zealand in Clause 1.6.19 for greater k_C.

Finally ECNSW (now Transgrid) uses the following formula for horizontal clearances h at mid span:

$$h = 0{,}3\sqrt{f - 2{,}13} + 84000\sqrt{f}\,(d / W_{500})^2 + 0{,}0076\,U \qquad (1.7)$$

where:

f = sag at mid span (m);
d = diameter of conductor (m);
W_{500} = resultant load (N/m) due to gravitational load and wind pressure at 500 Pa;
U = RMS voltage between conductors (kV).

1.6.2 Austria

If conductors are made of the same material, having the same cross-section and the same sag, it is permissible to determine the minimal distance c_{min} between the non-deflected conductors in the middle of a span from the experimental formula:

$c_{min} = k_C \sqrt{f + l_{ins}} + K \cdot D + b > 0{,}8$ m (1.1) (expressed in m) with:

- factor k_C given in Table 1.3;
- sag f measured at 40°C;
- second term $K{\cdot}D$ replaced with Z given in Table 1.5 for phase to phase clearances.

For calculations of deviations of suspension strings equipped with or without counterweights wind force on conductors may be reduced for spans exceeding 200 m as follows: $G_L = 0{,}6 + 80 / L$ where L (m) is the arithmetic medium value of the adjacent spans. For the swing angle of an ice free conductor a wind speed of 33,33 m/s (120 km/h) is considered.

For conductors arranged one above the other and not deviated, the horizontal distance is at least Z.

Moreover the vertical distance v between conductors arranged one above the other and not deflected, is not less than:

$$v = 1{,}70 \cdot \Delta f + Z \qquad (1.8)$$

where:

Δf the difference between the sag of the upper conductor with exceptional ice load at -5°C and the lower conductor without additional ice load (m).

Where two neighbouring live conductors are kept apart in a span by means of interphase spacers resulting in subspans, distances between conductors may be reduced.

1.6.3 Belgium

In case of similar conductors with same material, cross-section and sag, the empirical formula for the minimum distance between conductors in wind still conditions:

$$c_{\mathrm{min}} = k_{\mathrm{C}} \sqrt{f + l_{\mathrm{ins}}} + K \cdot D + b \qquad \text{(1.1) (expressed in m)}$$

may be used with:

- factor k_{C} given in Table 1.3;
- sag f measured at 40°C;
- second term $K{\cdot}D$ replaced with $0{,}75{\cdot}d_{\mathrm{m}}/\sqrt{3}$ for phase-to-earth and $0{,}75{\cdot}d_{\mathrm{m}}$ for phase-to-phase clearances where d_{m} = 0,50; 1,05; 1,55; 2,70 respectively for the nominal voltage of 70 kV; 150 kV; 220 kV; 380 kV according to Table 1.5.

In case of conductors with different cross-sections, materials or sags the higher factor k_{C} from Table 1.3 and the higher sag f are used.

If circuits with differing operational voltages run in parallel on the same structures, then the more unfavourable value for d_{m} is used. In addition to the distances for conductors in still air the clearances between swung conductors are also investigated. One conductor has to be considered to be swung out at all angles due to wind loading up to its maximum swing angle and at the same time the other conductors are to have a wind load + or - 40% that of this conductor.

The clearances at tower are based on the length of the air gap between arcing horns in the insulator set, say G, related to the basic insulation level:

- For load case 1: G = 1.25;
- For load case 5: G = 1.10;
- For load case 6: the minimum clearance is $U_{\mathrm{R}}/150$.

The horizontal offset between the attachment points at different levels is at least 0,20 m to take into account ice dropping.

The vertical distances between the twin conductors of all 380 kV lines are determined by galloping criteria. For a mean span of:

- 450 m, the vertical distance is 9 m;
- 520 m, the vertical distance is 11 m;
- 590 m, the vertical distance is 13 m.

1.6.4 Brazil

In Brazil the three basic voltage types are employed in insulation coordination studies for each new tower design specification, namely: power frequency voltage, fast front overvoltage and slow-front overvoltage. Criteria for swing angles are taken into account for each of those voltage types (See also Tables 1.5 and 1.6).

Fast front withstand voltage is specified based on the performance index required for the line (number of line outages per 100 km and per year) at any system voltage level. For EHV lines (245 kV and above) a similar procedure is applied to slow front withstand voltage. It is based on the PFO (Probability of Flashover), for which the Brazilian practice consists in establishing the maximum acceptable PFO (The figures specified for the PFO usually are in the range of 10^{-2} to 10^{-4}. It means that one line outage will be accepted in the range of 100 to 10 000 switching operations).

While for HV lines, the power frequency and fast front overvoltages prevail in the insulation design, slow front and/or fast front overvoltages may govern the insulation for EHV lines. This is an apparent anomaly toward European practice, because of the predominantly high keraunic levels in Brazil.

Being considered in all cases, power frequency voltages may, in some cases, govern parts of the insulation design, when the swing angles are taken into account. Power frequency voltage is usually considered for a 50 year return period wind, with period of integration 30 seconds.

Regarding clearances and swing angles, the Brazilian practice is based on the premises briefly described below.

For the phase-to-phase clearances at mid span between conventional towers, the world practice [7] has been adopted for the conventional lines in Brazil. They are determined by the known formula:

$c_{\min} = k_C \sqrt{f + l_{\text{ins}}} + K \cdot D + b$ (1.1) (expressed in m),

where the variables have the same meanings as given by the other countries.

Phase-to-earth clearances are determined by formulae, which provide values similar to the ones determined by European Standard. Their use, together with the respective swing angles for vertical strings, has resulted in satisfactory performance of the lines along the years.

However, if the clearances are approximately the same as in Europe, a point that differentiates Brazilian design practice has been the use of the Hornisgrinde approach [5] for determining the swing angles, as summarized in Reference [6], Chapter 11, page 535 and forth (See also clauses 2.2.3 and 2.9 as well as Figures 2.1, 2.4 and 2.5 in this TB).

Figure 1.1 - *500 kV compact racket tower in Brazil*

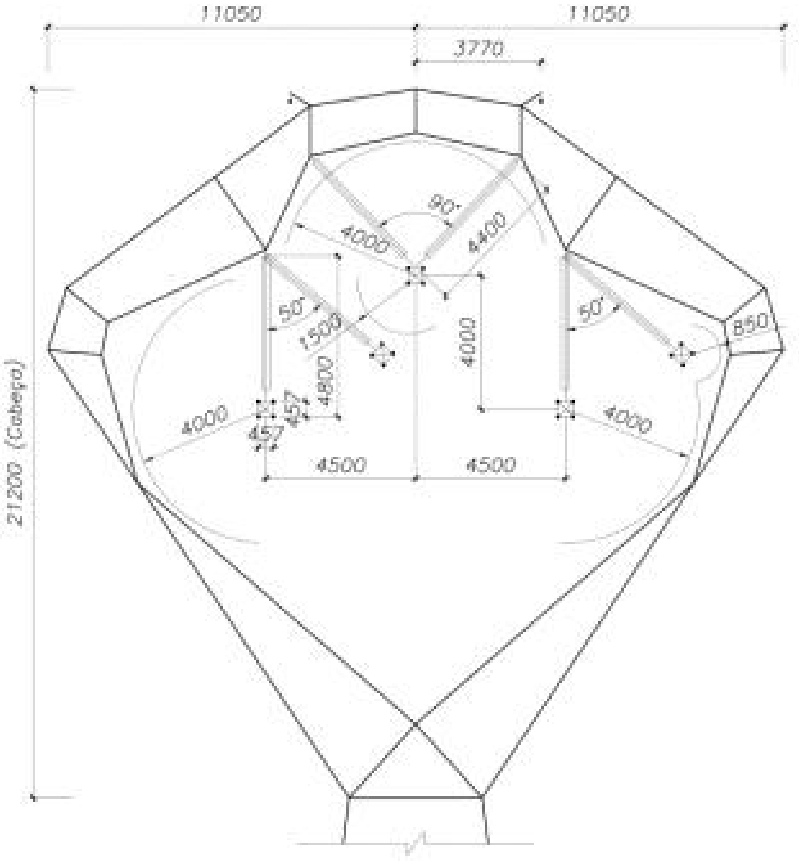

Figure 1.2 - *Swing angles and clearances for the compact racket 500 kV tower*

This method shows, based on experimental measurements and tests, that the swing angles of the insulator strings are usually much lower than the values normally taken into account, especially because of the wind fronts which are narrower than the values previously considered.

The introduction of compact lines in Brazil has forced the development and application of new techniques for increasing the capacity and simultaneously reducing the cost for the transmission of the same power. The development of compact lines necessitated trying to reduce the mid span clearances inside a safe range. A compact tower for 230 kV using a “racket” type concept was applied in about 1400 kilometres of single circuit lines in Brazil.

However, the development of 500 kV compact lines in Brazil, having started at the end of the eighties, was more impressive. It was especially aimed at increasing the transmission line capability because the need of long lines in Northern Brazil made it difficult to carry high powers at a reasonable cost, as the stability limits are a function of the line length and Surge Impedance Loading (SIL).

Among the available tools to increase the SIL of the lines, it seemed more advisable to develop compact towers. The first compact design was based on a “racket” type tower. This self-supporting tower presented already a significant degree of compaction and therefore permitted to increase the Surge Impedance Loading from the range of 950 - 1000 MW to 1200 MW, thus representing a significant economical gain. The first 500 kV compact tower designed and implemented in a 500 kV line of a length of 325 km was a self-supporting racket type tower. **Figure 1.1** shows a photo of this tower type and **Figure 1.2** the tower top geometry.

However, it was felt that another enough reliable and more economical tower could be developed with the same capacity. Thus, when the Utility of the area felt the need to build a second circuit parallel to the first one, with the construction of more around 1000 km at the same region, it seemed worthwhile to restudy the line configuration, aiming at eventually obtaining some savings while keeping the same performance. Other tower silhouettes were investigated, chiefly some cross-arm less designs. After a set of technical, experimental and economical studies, a cross rope tower was selected as the most appropriate for the new lines. Today 1665 km of 500 kV lines are in operation using this very compact cross rope tower type. Their performance has been quite satisfactory. **Figure 1.3** shows an illustrative photo of the cross rope tower. The swing angles and clearances of the basic 500 kV compact tower geometry, discussed above, are summarized in **Figure 1.4**.

Special considerations for compact lines, using experimental data, were applied, aimed at permitting a reasonable degree of compaction and at obtaining values, which could assure a good line performance along the years. As a result thereof, the cross rope tower, with horizontal configuration, was developed and designed in Brazil. An example for the 500 kV line using compact “cross rope” towers is given here under.

Figure 1.3 - *500 kV Compact cross rope suspension tower*

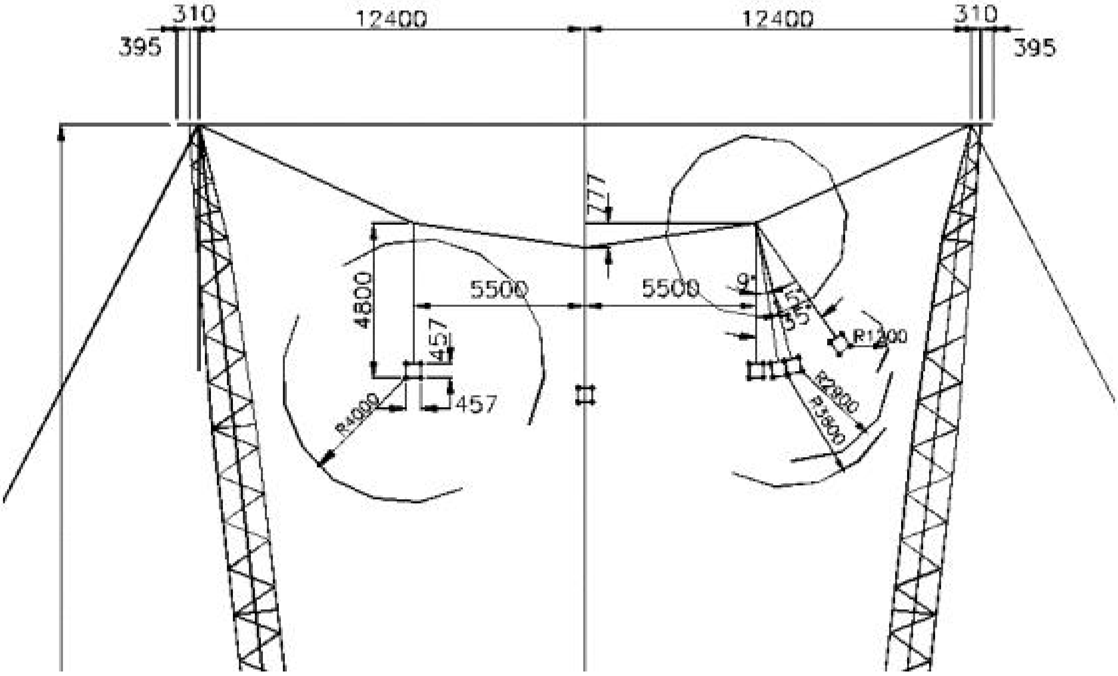

Figure 1.4 - *Clearances and swing angles at a typical compact cross rope tower*

A quadruple conductor bundle ACSR 483/33 mm^2 (Rail), spaced at 0,46 m was determined as the optimum conductor for compact lines, with a phase spacing around 5,5 m in order to obtain the required SIL. Only power frequency clearance was used considering asynchronous swinging of the phase conductors. No allowance was in principle added for other overvoltage types, which would require higher clearances, because of transitory conditions of other voltage stresses. If the traditional practice and tower types were used when a minimum phase-to phase spacing at least 7 to 8 m at the tower would be required, so that the necessary SIL would not be reached.

A deep study of the available technical literature on the subject especially of reference [18], showed that the differential conductor motion may be neglected, anyway would not exceed about 3° to 4°. It has been shown that a differential conductor motion until 9° would be acceptable for the phase spacing of 5,5 m.

A summary of the insulation coordination study for determining phase-to-earth clearances and the respective swing angles applied to compact 500 kV lines using cross rope towers is given below and characterized in Figure 1.4:

- Power frequency performance, minimum clearance and swing angle: the wind speed adopted for swing angle determination has been a 50 year return period value, with an integration period of 30 seconds. The probability of failure was taken as a maximum of 1 flashover in 30 years of line operation, which corresponds to a resultant probability of failure of $2{,}7 \cdot 10^{-5}$. The maximum operating voltage and 3 times the standard deviation were considered. According to the Hornisgrinde approach, the swing angle reached the value of 35°, considering the combination of the maximum wind speed and the maximum deflection angle of 2° for the tower application. The minimum required phase-to-earth clearance was determined in the range of 0,95 m to 1,05 m, when using either the EPRI Book [6] or the European Standard EN 50341-1[8] (a value of 1,20 m was conservatively applied in the design).

- Switching surge performance, minimum clearance and swing angle: the wind speed adopted for swing angle determination has been a reduced value corresponding to 60% of the 50 year return period value, with an integration period of 30 seconds. Two approaches have been used in such case:

    - For purpose of tower design a swing angle was determined as 12° (value adopted: 15°) and minimum clearances were determined by a formula developed in the seventies by Luigi Paris (the Cenelec formula gives comparable results), taking into account a maximum slow front surge of 2,2 p.u, referred to Base Voltage. Considering a climate factor of 0,95 the phase-to-earth clearances was determined as 2,90 m.

    - It was additionally specified that the line should have a slow front performance measured by the PFO as set in the table below. For assessing the PFO, a probability methodology was developed and applied, by calculating the probability of failure to every tower surface, to a complete tower, and finally to a certain number of towers (usually the number 50 is representative of the population at every line). A comparison between the specified and the assessed values is shown in **Table 1.9**. It can be seen that the line will have a much better performance than specified.

Table 1.9 – Comparison of the required and specified values of PFO for compact towers in Brazil

Switching surge	Phase-to-earth		Phase-to-phase	
	Required	Achieved	Required	Achieved
Energization	10^{-3}	$< 10^{-7}$	10^{-4}	$< 5 \cdot 10^{-6}$
Reclosing	10^{-2}	$<10^{-7}$	10^{-3}	$< 10^{-6}$

- Fast front performance, minimum clearance and swing angle: no wind is considered in this case. A swing angle, due to the conductor tension, corresponding to the maximum line deflection of 2°, was determined as 7,9° (Value adopted 9°). A minimum phase-to-earth clearance of 3,32 m was determined according to EN 50341-1. Finally a value of 3,60 m, equal to the insulator string length, was used for improving the line performance under lightning strokes.

In order to study the viability of phase compaction the key point taken into account was therefore the differential conductor motion. The curve of **Figure 1.5** is a summary of a series of experiments carried out to determine the minimum allowable phase spacing between conductors in relation to the maximum operating voltage in a span of 650 m. According to the same reference, it should be emphasized that there is no record of line trip-outs due to differential conductor movement induced by wind even with longer spans and small phase spacings. According to Figure 1.5 a minimum phase spacing of 4,1 m would be enough for a 500 kV line with a span of 650 m.

The viability of live line maintenance was examined and studied both theoretically and experimentally. Real mock-up tests were carried out, showing that the tower was able to accept live line work with total safety to the workers. After several years of operation, all lines provided with compact towers have presented an excellent performance and no line trip-out has been recorded due to phase-to-phase flashovers.

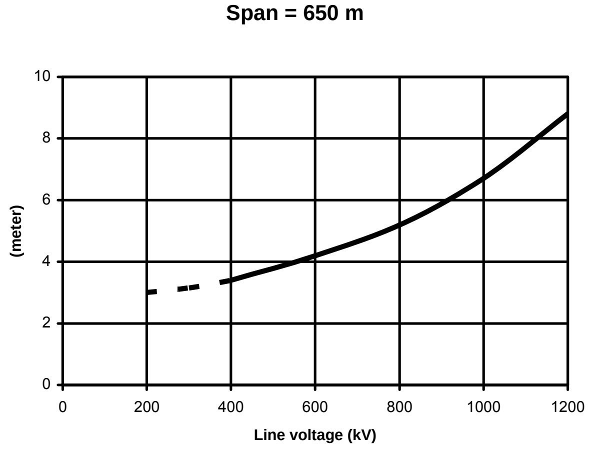

Figure 1.5 – *Relation of line voltage (kV) to phase spacing (m) for a span of 650 m*

1.6.5 Czech Republic

Twelve load cases are selected in the Czech Standard to determine internal clearances. The load cases and the corresponding clearances are summarized in Tables 1.5 and 1.6.

At mid span the clearance between conductors or between a conductor and the earth wire is at least:

$c_{\min} = k_C \sqrt{f + l_{\text{ins}}} + K \cdot D + b$ (1.1) (expressed in m) with:

- factor k_C > 0,54. Factor k_C depends on the diameter and the linear weight of the conductor and on the angle between both conductors. It is calculated according to a complex formula given in EN 50341-19;
- sag f measured at 40°C or at -5°C with reference ice load;
- coefficient K = 0,60 in the second term $K \cdot D$ where D equals D_{pe} for phase-to-earth clearance and D_{pp} for phase-to-phase clearance (See Table 1.5).

If values of k_C and f are different for both conductors, the greater of the clearances is decisive, as calculated for both conductors.

Some specific requirements are specified directly by the customer.

1.6.6 Denmark

The horizontal deviation of the conductor, d_s, under wind influence at mid-span is determined as follows:

$$d_s = k_C \cdot (f + l_{\text{ins}}) \qquad (1.9)$$

where sag f is measured at 0°C and factor k_C depends on the conductor material only:

- factor k_C = 0,70 for conductors of copper or steel (for swing angle $\varnothing$ = 45°);
- factor k_C = 0,85 for other conductors (for swing angle $\varnothing$ = 58°).

For suspension insulators at the tower, an insulator swing angle $\varnothing = 45°$ is applied. If the suspension insulator is located much lower than its neighbour towers, additional insulator swing must be considered.

Three different load cases are considered in Denmark (Tables 1.5 and 1.6):

- Maximum design temperature in still air (D_{pe}, D_{pp});
- Conductor swing (0,7 D_{pe}, 0,7 D_{pp});
- Galloping conductor (D_{pe_pf}, D_{pp_pf}).

During galloping an additional sag of $\Delta f = 0{,}50\ f$ at 0°C is considered.

1.6.7 Estonia

The load cases for the internal clearances are summarized in Tables 1.5 and 1.6.

Clearances D_{pe} and D_{pp} by wind load of three year return period may be reduced by $k_1 = 0{,}75$. For the load case “Extreme wind load” the return period is 50 years.

Combined ice and wind loads need not to be taken into account in the determination of clearances.

For calculation of clearances the galloping of conductors and earth wires is taken into account. The method of calculation is specified in the Project Specification.

1.6.8 Finland

The clearance between the clamping points of phase conductors and between phase conductors and earth wires is calculated as follows:

$c_{min} = k_C \sqrt{f + l_{ins}} + K \cdot D + b$ (1.1) (expressed in m) with:

- factor $k_C = 0{,}6$ for the horizontal configuration and $k_C = 1{,}0$ for the vertical configuration, independent of the swing angle;
- sag f measured at 50°C;
- coefficient $K = 1{,}00$ in the second term $K \cdot D$ where $D = D_{pe}$.

When the conductors are in neither configuration mentioned above, their horizontal component h_c and vertical component v_c is chosen so that the following inequality is fulfilled:

$$h_c/h + v_c/v \geq 1{,}2 \qquad (1.10)$$

where h ($\geq D_{pe} + 0{,}5$ m) and v ($\geq D_{pe} + 0{,}8$ m) are the values for c_{min} above for respectively the horizontal (or if $v_c \leq 0{,}2\ v$) and vertical (or if $h_c \leq 0{,}2\ h$) configuration.

In case of two dissimilar conductors, e.g. phase conductor and earthwire, the clearance is calculated using the bigger sag.

When determining clearances, not all the different load cases are taken into consideration, such as combined wind and ice load.

For the mid span clearances it is not required to consider e.g. the case where one conductor is in ice load and the other without ice. However, the normal utility practice has been to examine also the above mentioned case where there is ice on the earth wire and no ice on the phase conductor since that situation has caused some problems in the network. Therefore, usually in the Project Specification the requirement is that in the aforementioned situation the spacing between dissimilar conductors in mid-span is at least 0,5 m + D_{pe}.

The permanent conductor elongation due to all the load cases given in Table 1.6 and creep are taken into account.

Combined ice and wind loads are not taken into account in the determination of clearances.

The consideration of corona effect may lead to much higher clearance requirements than those in the calculations above. This may be allowed for in Project Specifications.

1.6.9 France

The spacing between conductors at mid span is not less than:

$c_{\mathrm{min}} = k_{\mathrm{C}} \sqrt{f + l_{\mathrm{ins}}} + U / U_0 + b$ (1.3) (expressed in m) with:

- factor k_{C} = 0,6; in case of ice, k_{C} = 0,6 is multiplied by the ratio of the resulting weight of conductor with wind and ice / weight of the conductor;
- sag f measured at 15°C;
- second term U / U_0 replaced with $U_{\mathrm{R}} \sqrt{3}$ / 400 for phase-to-phase clearances and U_{R} / 400 for phase-to- earth clearances.

If $f + l_{\mathrm{ins}} > 80$ m, the first term $k_{\mathrm{C}} \sqrt{f + l_{\mathrm{ins}}}$ is replaced with $(f + l_{\mathrm{ins}})/30 + 2,7$; in case of ice, it is multiplied by the ratio of the resulting weight of conductor with wind and ice / weight of the conductor.

It is advised to use tower cross-arms with horizontal arranged conductors.

Anyway, the horizontal distance between vertical planes which pass through the conductors located on superposed cross-arms is at least equal to the minimum clearances defined above. The minimum horizontal distances are:

- conductor-conductor : 0,70 m;
- conductor-earth wire : 0,40 m.

If these distances are fulfilled, the ice discharge checking is not necessary, even if this assumption is defined in the Project Specification.

For ice conditions without wind, the clearance between upper and lower conductor are checked with differential ice loading at -5°C: the upper conductor covered with ice thickness (2; 3; 4; 5 or 6 cm depending on the ice zone) chosen for calculating the structure; the lower conductor covered with ice thickness that is:

- half of upper conductor if it is a phase conductor;

- quarter of upper conductor if it is an earth wire.

The Project Specification may require additional checks under partial ice overload for ice sleeve thickness exceeding 4 cm and spans longer than 800 m.

Other assumptions may be defined in the Project Specification, such as :

- unbalanced icing overload,
- partial icing overload,
- ice discharge.

The clearances between earthed parts of the tower and live parts (conductors, jumpers, counterweights) are checked under the following assumptions (Tables 1.5 and 1.6):

- temperature of 15°C and still air;
- low wind pressure (240 Pa in AZVN area and 360 Pa in AZVF area) at 15°C;
- extreme wind pressure (800 Pa) for suspension towers only.

Minimum clearances for live line working methods are defined in Project Specifications.

Additional checks for short-circuit current may be required in Project Specifications.

1.6.10 Germany

In case of identical conductors within a span the approximate formula (1.1) for evaluating minimum clearances in the middle of the span may be used. The minimum clearance $c_{\min}$ of the conductors at mid-span measured in still air is at least:

$c_{\min} = k_C \sqrt{f + l_{\mathrm{ins}}} + K \cdot D + b$ (1.1) (expressed in m) with:

- factor k_C given in Table 1.3;
- sag f measured at 40°C. The effect of the wind load on the conductor sag may be neglected;
- coefficient $K = 0{,}75$ in the second term $K \cdot D$ where D equals D_{pe} for phase-to-earth clearance and D_{pp} for phase-to-phase clearance (See Table 1.5).

If circuits with differing operational voltages run in parallel on the same structures, then the most unfavourable value for D_{pe} or D_{pp} is used.

In the case of conductors with different cross sections, materials or sags the higher factor k_C from Table 1.3 and the higher sag is used.

In this case, a clearance not less than 0,75 D_{pe} or 0,75 D_{pp} is kept between swung conductors. For this investigation, the design wind speed (pressure) for the determination of electrical clearances is 75% (58%) of the wind speed (pressure) for the mechanical design. Those wind speeds have respectively a return period of 3 and 50 years. Moreover, wind pressures differing by 40% are acting on the individual conductors.

The verification of clearances under extreme wind conditions with a return period of 50 years is not required. Similarly, a verification of clearances under simultaneous action of wind and ice is not required by the German Standard.

When calculating clearances under ice load conditions the conductor temperature is assumed to be constant at –5 °C. Ice loads are created by accretion due to hard rime, precipitation icing or wet snow at the conductors. Concerning the design ice loads, three different ice zones are identified based on the climatic conditions, the geographical situation and confirmed by long-term experience regarding the impact of ice loads on overhead lines. As uniform ice loads don't change the relative positions of identical conductors, ice load conditions are not considered for internal clearances.

When evaluating the clearances at the tower, the swing angle is considered for deflection of the insulator set, which results from the ratio of the wind load (with a return period of 3 years) acting on the conductor and insulator set to the dead load of the conductor and the insulator set.

In case of angle suspension towers the resultant of the conductor tensile forces under wind load and at +5°C are considered in addition to the wind loads on conductors.

1.6.11 Great Britain

For normal electrical clearances, the 3-year return values are used. These can be approximated by the application of a value of 0,75, applied to the 50 year return wind speed and ice thickness values.

Alternative methods may be adopted providing that these can be shown to be justified by long and satisfactory service history in similar environments. They are defined in the Project Specification.

Maximum differences in wind loading, ice loading, and conductor temperature that are assumed between adjacent conductors are specified in the Project Specification.

If the reliability based design method is not used for the design of overhead lines, such as for (some) wood pole lines, clearances are defined in Project Specifications.

1.6.12 Greece

The clearances between earthed parts of the tower and the live parts are not lower than the limits indicated in Table 1.5 for the wind conditions indicated in Table 1.6:

• Still air	1,3 m (150 kV)	2,8 m (380 kV)
• Low wind (pressure 190 N/m2)	1,1 m (150 kV)	2,4 m (380 kV)

• Strong wind (pressure 430 N/m2)	0,9 m (150 kV)	1,2 m (380 kV)
• Extreme wind (pressure 765 N/m2)	0,5 m (150 kV)	0,8 m (380 kV)

1.6.13 Iceland

Six cases are considered for calculation of clearances:

- Still air;
- Wind load with a 3 year return period (gust wind);
- Wind load with a 50 year return period (gust wind);
- Uniform ice load with a 50 year return period;
- Differential ice load (unbalanced ice load): maximum ice on one span and other spans free of ice;
- Unbalanced ice load in three spans.

For the combined wind and ice load, the following load is considered:

- Ice load with a 30 year return period;
- 50% of wind load with a 50 year return period (gust wind).

The clearances are given in Tables 1.5 and 1.6. The internal clearance required under still air conditions are maintained 99% of the time.

Galloping of conductors and earth wires are considered for calculation of clearance within the span, as specified in Project Specification.

1.6.14 Ireland

The swing angle ϕ and the corresponding clearances *D* at the tower are given below:

	Swing angle ϕ		Clearances *D*		
	110 kV	220-400 kV	110 kV	220 kV	400 kV
Intermediate tower insulator	50°	52,5°	0,75 m	1,00 m	1,75 m
Angle tower jumper	45°	17,5°	0,75 m	2,00 m	3,50 m
	0°		1,40 m		

1.6.15 Italy

The spacing between conductors at the points of connection to the towers is not less than: $c_{\min} = k_C \sqrt{f + l_{\text{ins}}} + U / U_0 + b$ (1.3) (expressed in m) with:

- factor k_C = 0,6 or 0,5 according to the conductor type:
  - k_C = 0,6 for homogeneous aluminium or aluminium alloy conductors;
  - k_C = 0,5 for other conductors;
- sag *f* measured at 15°C;

- second term U / U_0 replaced with $U_R/100$ for phase-to-phase clearances.

The above mentioned formula does not apply to spans of lines where $f + l_{ins} > 40$ m. In such cases it is merely necessary that the spacing between the conductors is not less than:

- $(3{,}8 + U_R/100)$ m for aluminium or aluminium alloy conductors;
- $(3{,}2 + U_R/100)$ m for the other conductors.

In spans over 900 m and conductor bundles single phase towers are used to increase the clearance.

The minimum distances between live parts and earthed parts of towers are given in Tables 1.5 and 1.6.

1.6.16 Japan

Japan is the only country that applies probabilistic principles for mid span clearances. Design practice adopted in Tohoku Electric Power Co. is shown below.

The required withstand voltage is determined by the standard deviation (σ) of flashover voltage and 50% flashover voltage. For example, required withstand voltage for switching surge is the value deducted 2-3 standard deviations (σ) from the 50% flashover voltage. The coefficients for standard deviation are determined according to the required reliability of the transmission line: 2 times for 275 kV and 3 times for 500 kV.

For power lines which pass special areas with severe natural conditions, for long span power lines and extra high voltage power lines of 275 kV or more, the horizontal deflection of conductors by the wind, which is probabilistic, is examined to define mid-span clearances. This method uses statistical analysis to determine the standard deviation and check the minimum distance in mid span, assuming that the change around the mean swing angle caused by the wind between conductors follows some probabilistic distribution.

Snow accretion is determined by considering a return period. It is based on company observation data near the power line, or on weather station observation data.

When sleet jump or galloping is a concern in newly constructed extra high voltage power lines of 275 kV or more, it is considered as one of the determining factors for minimum mid-span clearances. For sleet jump sufficient clearances can be ensured in most cases by preparing suitable offsets for tower configurations. However for galloping, sufficient clearances sometimes require quite large distances between conductors. Therefore it is common to adopt mitigation devices, like loose clamp spacers, etc., to reduce the distance.

Dynamic movement of a conductor by a short-circuit current is considered when designing a spacer for a multi-conductor bundle rather than examining mid-span clearances. When the lowest phase of a higher circuit has an earth fault due to a lightning accident, etc., sag increases since a very large earth fault current flows temporarily. But, because of high-speed re-closing by relay operation, or instantaneous fault removal of the fault section, earth fault current has a very short duration and the increase in sag does not become a huge problem.

Higher and lower circuits need to have a predetermined clearance which should be the sum of the clearance for both circuits to prevent electric failure. For example, it may be the sum of the clearance for switching surge (higher circuit) and the clearance for power frequency voltage (lower circuit).

Despite the narrow profile of Japan, snow accretion on strung conductors has various intensities and frequencies by areas. Also typhoons have various intensities and frequencies by areas. The elements which determine mid-span clearances are diversified by area.

1.6.17 Lithuania

The empirical equation: $c_{\min} = k_C \sqrt{f + l_{\text{ins}}} + U / U_0 + b$ (1.3) is applicable for horizontal conductors with:

- factor k_C = 0,6;
- sag f;
- second term U / U_0 replaced with U_R / 110 + 1,0 m for phase-to-phase clearances.

Required minimal phase-to-phase clearances, when conductors are not located horizontally in suspension towers and when galloping occurs once in 5-10 years, are given in specific tables.

1.6.18 Netherlands

The clearances under extreme wind conditions in the Netherlands are greater than those mentioned in European Standard EN 50341-1 as it is required that low-level switching overvoltages (≈ 1.3 p.u.) with a high probability of occurrence (90%) will be resisted, in stead of only the power frequency voltage.

Empirical equation: $c_{\min} = k_C \sqrt{f + l_{\text{ins}}} + K \cdot D + b$ (1.1) is applicable with:

- factor k_C = 0,6;
- sag f measured at 10°C without wind;
- second term $K{\cdot}D$ replaced with D_{pp} for both phase-to-earth and phase-to-phase clearances.

Clearance D_{pp} is the biggest distance resulting from the clearances to withstand switching and lightning overvoltages:

Overvoltage (kV)	350	550	750	950	1050	1250	1400
Clearance to withstand lightning overvoltage (m)	0,72	1,12	1,53	1,94	2,14	2,55	2,86
Clearance to withstand switching overvoltage (m)	0,83	1,44	2,17	3,06	3,56	4,72	5,75

Therefore clearance D_{pp} could not be associated directly with the highest system voltage U_s in Table 1.5.

In stead of defining a maximum conductor temperature as mentioned before, it is also allowed to define a lowest value of the catenary constant p_{min}, for which the line has been designed. The advantage of using p_{min} is that this design parameter is independent of conductor types and is related to the design limits (maximum sags) of the line.

For the determination of clearances at the tower the following load cases are considered:

- design wind load with 3 year return period, taking into account D_{pp_pf} from Table 1.5;
- extreme wind velocities with 50 year return period, taking into account D_{pp} given above.

Clearances D_{pp_pf} are greater than those mentioned in EN 50341-1 as it is required that low-level switching over voltages (≈ 1.3 p.u.) with a high probability of occurrence (90%) will be resisted, in stead of only the power frequency voltage.

For extreme ice loads a return period of 50 years in stead of 3 years is considered.

Due to the combination of wind and ice, galloping can occur. In case that galloping has to be considered, increased vertical and horizontal clearances are required.

If a tower has climbing devices, the distance to these devices is $\geq 1{,}1 \times D_{pp} + 1{,}60$ m taking into account a wind load, prescribed by the utility.

Short duration extreme conductor temperatures, due to short circuit currents need not to be taken into account.

1.6.19 New Zealand

For the Australian practices, ESAA Handbook C(b) 1 was already mentioned as it specifies a mid-span formula for horizontal, vertical and angular clearances between conductors:

$$c_{min} = k_C \sqrt{f + l_{ins}} + U / U_0 \qquad (1.6)$$

with:

- factor $k_C \geq 0,4$;
- sag f measured at 50°C;
- second term U / U_0 replaced with $U_R/100$ for phase-to-phase clearances.

In principle c_{min} in (1.6) has to be replaced with $\sqrt{h_c^{\ 2} + (1,2\ v_c)^2}$ where h_c and v_c are respectively the horizontal and vertical components of clearance c_{min}.

For normal calculations a k_C value of 0,4 is used, however this needs to be increased if any of the following circumstances exist:

- Extremely turbulent wind conditions;
- The different amount of movement of conductors of different size and type under the same wind conditions;
- Conductor movement under fault conditions (particularly with horizontal construction).

This equation is intended to cater for out-of-phase movement of conductors under wind conditions with minimum turbulence.

The formula for the phase-to-earth clearance is not available.

ESAA Handbook C(b)1-1999 adopts a risk management approach to determining probability of flashover, hence lines in built up areas have a higher electrical reliability than those located in isolated areas.

The absolute minimum clearances are stated in NZCEP 34:2001 ISSN 0114-0663 - New Zealand Electrical Code of Practice for Electrical Safe Distances. This code is mandatory in New Zealand for the clearances referred to:

110 kV and below	2,0 m;
Above 110 kV	2,5 m.

According to NZECP 34:2001, a fixed voltage line should have all the same minimum mid-span phase clearances.

However TP.DL 12.02 February 2002 (Transpowers Standard) also states that the minimum spacing in any circumstances shall be 0,40 m plus 0,01 m for each 1 kV in excess of 11 kV.

1.6.20 Norway

Conductors in the same horizontal plane have a minimum clearance within the span of:

$c_{min} = k_C \sqrt{f + l_{ins}} + K \cdot U + b$ (1.2) with:

- factor k_C = V_z/55 > 0,55 for suspension insulators and V_z/60 > 0,50 for strain or post insulators, where V_z is the mean wind velocity at height h above ground;
- sag f measured at 50°C;
- second term $K{\cdot}U$ replaced with $0{,}007{\cdot}U_S$ for both phase to earth and phase to phase clearances.

The factor k_C for angular and vertical positions is not available.

Conductors with a vertical separation are controlled for a load case with ice on the upper conductor and 0°C and no ice on the lower conductor while both conductors also are subjected to wind. The ice- and wind load in this case has a 3 year return period. The vertical separation between earth wire and conductor are controlled likewise.

The return period for ice load is specified in the Project Specification, but is not less than 50 years.

For galloping, the minimum clearance is normally in the range of 4-5 m for highest system voltage of 132 kV and 9 m for highest system voltage of 300 kV.

1.6.21 Portugal

The empirical equation: $c_{\min} = k_C \sqrt{f + l_{\text{ins}}} + K \cdot D + b$ (1.1) is applicable with:

- factor k_C = 0,6 or 0,7 depending on the conductor type:
  - o k_C = 0,6 for ACSR, AACSR, steel, copper and bronze;
  - o k_C = 0,7 for AAC and AAAC;
- sag f measured at 75°C;
- second term $K{\cdot}D$ replaced with D_{pp} for both phase-to-earth and phase-to-phase clearances. D_{pp} originate from EN 50341-1.

This clearance is also valid between conductors of different circuits.

1.6.22 Serbia

Empirical equation $c_{\min} = k_C \sqrt{f + l_{\text{ins}}} + K \cdot D + b$ (1.1) is applicable with:

- factor k_C depending on the swing angle and the relative position of conductors;
- sag f measured at 40°C;
- second term $K{\cdot}D$ replaced with D_{pp} for both phase-to-earth and phase-to-phase clearances.

In heavy ice loading cases it is usually to choose a horizontal line configuration.

1.6.23 Slovenia

In the process of verification of clearances in all cases of line crossing or adjacent to objects of greater importance, 58% of wind pressure at + 40°C is taken into account.

1.6.24 South Africa

In South Africa a semi-probabilistic method of determining tower top clearances is used. The values for clearances relating to lightning, switching and normal power frequency voltages all differ from each other for a given power frequency voltage. The clearance values are tabulated in the South African code of practice SABS 0280. A figure of ± 3 pu and ± 2,2 pu was used to calculate the overvoltages during lightning and switching. These overvoltages were used to calculate the required clearances. Values of corresponding clearances are confirmed through dielectric tests at high altitude (H = 1550 m), representing majority of South African conditions.

For conductor mid-span clearances, an empirical formula has been created and is indicated below:

$$c_{\min} = k_C \cdot \sqrt{\frac{(f + l_{ins})}{2}} \cdot \frac{\cos \alpha}{\cos \beta} + D + b \qquad (1.11)$$

where:

- factor k_C describing differential motion:
  - k_C = 0,70 for motion in average wind conditions;
  - k_C = 0,85 for motion in maximum wind conditions;
- second term D = phase-to-phase clearance:
  - $D = D_{pp}$ or the phase-to-phase safety clearance for the maximum expected overvoltage when k_C = 0,70 for average wind conditions;
  - $D = D_{pp\_pf}$ or the clearance for the highest system voltage, when k_C = 0,85 for maximum wind conditions;
- α = vertical angle between the conductors (^{0});
- β = angle of conductor in span inclination: 15°-20° for maximum overvoltage conditions, 55°-60° for power frequency default.

A probabilistic method is employed to determine an appropriate templating temperature. The probabilistic method for mid-span phase to ground clearance has become a utlity (Eskom) standard.

Minimum working live line clearances are also specified and are part of the clearances which dictate the tower configuration. The expected overvoltage level for the live line working conditions is calculated on a value of ± 1,8 pu, based on constraints in conditions during which live line work is allowed. No distinction is made between the required phase-to-phase clearance to be maintained while working at the tower or while working at mid span.

In South Africa, there is very limited application of ice loading due to the typically hotter climates. There was a research project that performed studies on the locations for ice loading in the country.

Ice loading however is not used .to determine the clearances at the tower or mid-span and is only accounted for mechanically.

1.6.25 Spain

The minimum separation between conductors is determined in accordance with the following approximate formula:

$c_{\mathrm{min}} = k_{\mathrm{C}} \sqrt{f + l_{\mathrm{ins}}} + U / U_0 + b$ (1.3) with:

- factor k depending on the swing angle:
    - o k_{C} = 0,60 for swing angle $\phi < 45°$;
    - o k_{C} = 0,65 for swing angle $\phi \geq 45°$ and $\leq 65°$;
    - o k_{C} = 0,70 for swing angle $\phi > 65°$;
- sag f measured at 50°C;
- second term U / U_0 replaced with $U_{\mathrm{R}}/150$.

In the case of different conductors or with different values of sag, the separation between them is justified, analyzing wind-induced oscillations.

In zones in which ice may be expected on particularly important conductors, special care is taken in analyzing the risk of inadmissible approximations between conductors.

1.6.26 Sweden

For the calculation of the mid span clearances Sweden uses various formulae.

For similar conductors distinction is made according to the relative position of the conductors:

- Horizontal configuration: the horizontal clearance between conductors $c_{\mathrm{min}} = h$ according to formula (1.12) below with uniform ice load on both conductors;
- Vertical configuration: the vertical clearance between conductors $c_{\mathrm{min}} = v$ according to formula (1.13) below with uniform ice load on the upper conductor and no ice load on the lower conductor;
- Angular configuration: the horizontal component h_{c} of the oblique clearance c_{min} is determined in function of the vertical component v_{c} and of h (1.12) and v (1.13) as well, according to formula (1.14) below and vice-versa.

For dissimilar conductors, different wind loads are considered on both conductors:

- A normal wind load on one conductor covered by uniform ice load increasing from zero to 100%;
- 70% of the normal wind load on the other conductor covered by uniform ice load increasing from zero to 100%.

For dissimilar conductors in angular position, the Standard proposes a graphic solution.

The minimum distance between both curves described by the sag and swing-out of the conductors under influence from dead weight and increasing combined ice and wind loads must be less than $K \cdot U_S$. Coefficient K and highest system voltage U_S are defined below. The wind is supposed to act in the most unfavourable direction. The calculation of the clearance between dissimilar conductors is made for the most unfavourable condition of sag before or “after” creep of the conductors.

If the dissimilar conductors are placed in a horizontal plane, formula (1.12) is replaced with formula (1.15) below for clearance $c_{min} = h_d$ where a uniform ice load is considered on both conductors with 100% of the normal wind load on one conductor and 70% of the normal wind on the other conductor. This clearance is calculated for both wind directions. For the vertical configuration of dissimilar conductors, formula (1.13) for equal conductors may be used.

The formulae for the clearances h, v, h_c, v_c and h_d for similar conductors are:

$$h = k_C \sqrt{f + l_{ins}} + K \cdot U_S + b \qquad (1.12)$$

$$v = (k_v \cdot \Delta f + \Delta l_{ins}) + K \cdot U_S + b \qquad (1.13)$$

$$h_c = h \sqrt{1 - (v_c/v)} \quad ; v_c = v\,[1 - (h_c/h)^2] \qquad (1.14)$$

$$h_d = \Delta[(f + l_{ins}) \cdot \sin \phi] + K \cdot U_S + b \qquad (1.15)$$

where:

- h is the horizontal clearance between similar conductors in a horizontal configuration (m);
- v is the vertical clearance between similar conductors in a vertical configuration (m);
- h_c is the horizontal component of the clearance c_{min} between similar conductors in an angular configuration (m);
- v_c is the vertical component of the clearance c_{min} between similar conductors in an angular configuration (m);
- h_d is the horizontal clearance between dissimilar conductors in a horizontal configuration (m);
- k_C is a factor for horizontal configuration, which is 0,45 (-);
- k_v is a factor for vertical configuration, which is 1,1 for ACSR, AAC and AAAC conductors and 1,3 for copper and steel conductors with a suspension insulator set (-). For dissimilar conductors the highest value of the two conductors is chosen;

- f is the sag of the conductor with uniform ice load and no wind (m);
- Δf is the difference of the sag between a conductor with uniform ice load and a conductor without ice load (m);
- l_{ins} is the mean length of the suspension insulator set swinging orthogonal to the line direction (m);
- Δl_{ins} is the difference between the mean length of the suspension insulator of the upper conductor and the mean length of the suspension insulator of the lower conductor (m);
- $\Delta[(f + l_{ins})\cdot\sin \phi]$ is the difference of the horizontal deviation of the sag of conductors with the same uniform ice load, but with a different wind load, respectively 100% and 70 % of the normal wind load (m) (where ϕ is the swing angle);
- K is a coefficient which is 0,006 for phase-to-earth clearance and 0,007 for phase-to-phase clearance (-);
- U_S is the highest system voltage (kV);
- b is the outside diameter (m) of the conductor bundle, if any.

The minimum air clearances at the tower are in accordance with Tables 1.5 and 1.6.

The clearance between energised parts of different phases are at least 1,15 times the values given for phase-to-earth clearance.

1.6.27 Ukraine

Empirical equation $c = k_C \sqrt{f + l_{\text{ins}}} + U / U_0 + b$ (1.3) is applicable for the clearance between conductors in horizontal arrangement:

- factor $k_C = 0{,}6$;
- sag f measured with maximum temperature or with ice load;
- second term U / U_0 replaced with:
  - $U_S / 110 + 1{,}0$ m for $U_R < 500$ kV;
  - $U_S / 150 + 1{,}0$ m for $U_R \geq 500$ kV.

For $U_R \geq 500$ kV the conductors are only in horizontal configuration.

If the conductors for $U_R < 500$ kV are not in a horizontal configuration, equation (1.3) is still valid for sags $f > 16$ m if second term U / U_0 is replaced with:

  - $U_S / 110 + 1{,}0$ m $+ 0{,}15\ v$, where v is the vertical distance between conductors.

If the sag f is lower than 16 m a synoptic table is used for interpolation.

The return period of the climatic loadings considered is:

- 5 years for 0,4-1 kV;
- 10 years for 1-35 kV;
- 15 years for 110-330 kV;
- 25 years for 500-750 kV.

1.7 Conclusion

The existing practices for definition of tower top geometry mostly refer to National Standards or Codes.

Generally, the geometric dimensions in tower top depend on:

- The vertical distance between conductors, that is mainly determined by the “still wind conditions” at tower, except if galloping or differential ice load is considered;
- The horizontal length of the cross-arms to the first conductor, that is mainly determined by the “swung conditions” at tower;
- The horizontal distance between conductors, that is mainly determined by the differential “swung condition” at mid-span;

The approach presented in the following Parts 2 to 5 for the design of the tower top geometry complies with these aims and represents an improvement on the various empirical methods in use for this purpose.

Part 2: Determination of swing angles of conductors and insulator sets

2.1 Introduction

Tower top geometry is determined by the clearances required between conductors of differing phases at mid span and between live conductors and the earthed structures under various electrical conditions. The available clearances depend on the conductor and insulator position. The position of conductor and of I-type suspension insulator strings at suspension towers varies under wind action. The wind load causes swinging of the conductors and I-type insulators, thus reducing the clearances.

The issue of clearances between I-string insulator positions at suspension towers has been dealt with in the CIGRE Technical Brochure No. 48 [1]. The spacing of conductors on the tower must be wide enough to avoid clashing or flashovers in mid-span. Therefore, the mid-span clearances govern the spacing of the conductors at the structures. This aspect is dealt with in this document.

The wind action varies with time and space and can be described as randomly distributed using statistical approaches [1; 2; 3; 4]. The time-dependent conductor position will be randomly distributed as well. Additionally, the swing angles of insulators depend on line parameters such as ratio of wind span to weight span, conductor type, etc. This Part 2 of the document aims at compiling the material on swinging of conductors due to the wind loads, which is available to the Working Group 06 of SC B2, and proposing an approach for determination of conductor and insulator positions to establish tower top geometry.

2.2 Parameters involved

2.2.1 Wind velocity

The wind velocity varies with time and space. With reference to the line the wind velocity varies along the span and with the height above ground level. To determine the conductor and insulator position depending on the wind it is necessary to consider the distribution of the wind velocity along the span and the variation with the height above ground level. Additionally, the wind direction is important as well.

To assess the time distribution of the conductor and insulator position knowledge of the time distribution of wind speed is necessary.

2.2.2 Wind direction

The component of the wind velocity acting perpendicularly to the conductors causes swinging of conductors and insulators. Wind statistics often comprise only wind velocity values independent of the wind direction. To assess the probability of swing angles it is necessary to take appropriate note of the wind direction.

2.2.3 Relation between wind velocity and swing angle

If the wind acted steadily along the line and constantly over a longer period of time, the calculation of swing angle would be just a simple matter. However, in reality the fluctuation of wind affects the swing angle considerably. The peak gust wind velocities acting for 2 s will not cause swing angles statically equivalent to the locally observed peak gust wind velocity.

Conductors and insulators possess a certain mass which has to be accelerated first over the full span and moved into a stable swung position before the wind force on the span can be transmitted to the support. Therefore, peak gust wind velocities of short duration will affect neither the swing angles nor the forces acting on the towers. Only the mean values of wind velocities taken over a sufficient long period of time affect the average or visually observed swing angle. This fact can be observed directly on overhead power lines. Even in heavy storms with directly discernible gusts the insulators will remain in an apparent swung, stable position without clearly reacting to individual gusts.

Accordingly, various investigations of insulator swing angles indicate that the measured swing angles, on average, are smaller than those theoretically expected from the recorded instantaneous peak wind speeds [5; 6], and adopting the basic relations between wind forces on conductors and insulators.

In **Figure 2.1** records taken from [5] are shown from swing angles of insulator sets and in comparison with data calculated according to:

$$tg\,\phi = \left[\, n \cdot (\rho/2) \cdot V_{\mathrm{p}}^{2} \cdot C_{xc} \cdot d \cdot L_{\mathrm{W}} + F_{\mathrm{Wins}}/2 \,\right] / \left(n \cdot W_{C} + W_{\mathrm{ins}}/2 \right) \tag{2.1}$$

where:

ϕ swing angle of insulator;
n number of sub-conductors;
ρ air density, see (2.11);
V_{p} recorded peak gust wind speed;
C_{xc} drag coefficient for conductors to be assumed as 1.0;
d conductor diameter;
L_{W} wind span;
F_{Wins} wind load on insulator set;
W_{C} vertical conductor weight;
W_{ins} weight of insulator set.

Figure 2.1 confirms that the relation between wind velocity and swing angle needs deliberate consideration to achieve agreement between calculation and observation.

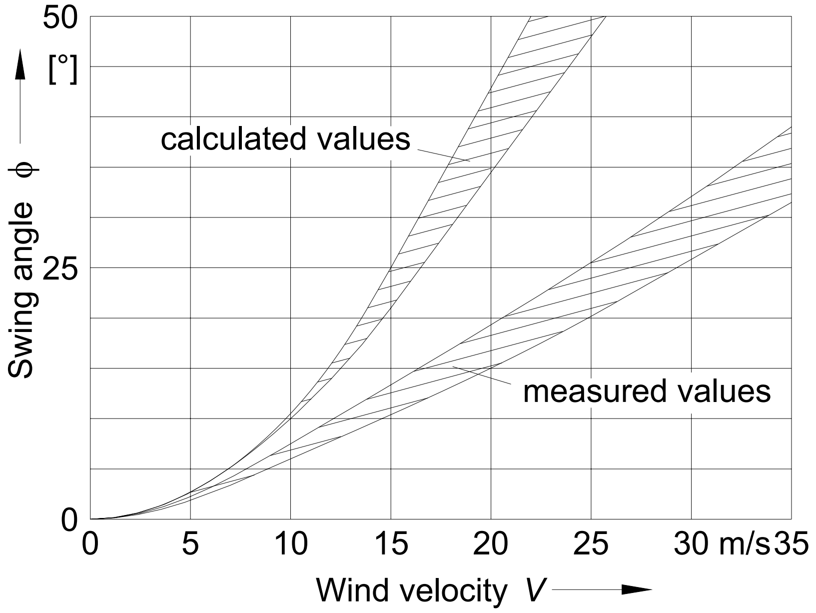

Figure 2.1 - *Calculated and measured swing angles ø (degrees) depending on the instantaneously recorded wind velocity V (m/s) according to [5]*

When calculating the swing angle ratio between wind span and weight span, as well as the span length and the type of terrain have to be considered. Peak gust wind velocities do not act on the full span length. Therefore, an additional parameter should be used to take adequate care of the span length. Proposals can be found in [7] to [10]. The action of wind on the conductors depends on the drag coefficient which varies with the relevant Reynolds number. For bare stranded conductors a drag coefficient of 1,0 is adequate [7; 8].

In order to achieve sufficient agreement between calculations and measurements the climatic data such as air density have to be duly considered, too.

2.3 Time distribution of wind velocities

To determine the time distribution of swing angles, it is necessary to know the time distribution of wind velocities.

2.3.1 Distribution of yearly maximum wind velocities

According to Annex B.2 of IEC 60826 [7] the probability of yearly extreme values of wind velocity may be described by the Gumbel distribution:

$$P(V_{obs} > V) = 1 - \exp\left[-\exp\left(-\pi\left(V - \overline{V} + 0{,}45\sigma_V\right)/\left(\sigma_V \cdot \sqrt{6}\right)\right)\right] \tag{2.2}$$

where:

$\overline{V}$ means the mean value of yearly maximum wind velocities;
σ_V is their standard deviation.

Formula (2.2) is valid for a large number of years with observations from which $\overline{V}$ and σ_V can be obtained. It represents the probability that the observed yearly maximum wind velocity V_{obs} exceeds a given value V. As reference for the determination of wind velocities averaging periods of 10 min or of one hour are used.

From this formula the wind velocity V_T corresponding to a given return period T (measured in years) can be determined:

$$V_T = \overline{V} - \sigma_V \left[0{,}45 + \left(\ln\left(-\ln\left(1 - 1/T\right)\right) \cdot \sqrt{6} \right) / \pi \right] \qquad (2.3)$$

2.3.2 Yearly time distribution of wind velocities

Equation (2.3) can be used to establish the wind velocity having a high probability of occurrence during one year, e. g. the wind velocity with a return period of two years, and to derive the yearly time distribution of the wind velocities based on this value.

The distribution of yearly maximum wind velocities and the time distribution have to be correlated adequately to achieve an acceptable and realistic image of the distribution of wind velocity during one year.

Regular measurements of wind velocities are performed throughout the year. They can be used to define the time distribution of wind speeds. In Europe and many other countries these measurements are usually averaged over 10 min. Assuming this averaging period, there are several procedures in use to carry out wind measurements:

(a) Readings are averaged every 10 minutes. During each year, 6 · 8760 = 52560 average values are recorded.

(b) Readings are averaged for one 10 minute period during each hour. 8760 values are recorded each year.

(c) Readings are averaged for one 10 minute period during every three hours. 8760 / 3 = 2920 readings are recorded per year.

(d) Readings are averaged for one 10 minute period during every six hours. 8760 / 6 = 1460 readings are recorded per year.

These systematic readings can be used to establish a time distribution of the wind speeds forming a basis for the determination of the time distribution of swing angles. The readings may also be used to establish statistics of extreme wind velocities which results in the parameters $\overline{V}$ (mean value of annual maximum 10 min wind velocities) and σ_V (standard deviation of annual maximum 10 min wind velocities) of formula (2.2).

In case (d), for instance, a wind velocity having a five year return period corresponds to one occurrence (reading) in five years, that is one reading out of 5 · 1460 = 7300 readings. This corresponds to a time probability of 1 / 7300 = $1{,}37 \cdot 10^{-4}$ per year. Or, during $1{,}37 \cdot 10^{-4} \cdot 8760 = 1{,}2$ hours per year, the wind velocity will be higher than the mentioned reading.

Case (b) (hourly readings) is often used but assumptions (d) should be used for relating extreme value statistic with time distribution of wind velocities because it is conservative for the purpose of assessing swing angles and conductor positions.

Further considerations to establish the time distribution of wind velocities are based on the wind velocity occurring once in two years and means one reading out of 2 · 1460 = 2920 values and corresponds to at time probability 1 / 2920 = $3{,}42 \cdot 10^{-4}$ during a year. During this time of the year the wind velocity will exceed the given reference value having a return period of two years. The statistical law for the time distribution of wind speed should give the same probability for this value.

It may be assumed that the yearly time distribution of the wind velocities follows the Weibull distribution [11].

$$P(V_{obs} < V) = \left\{1 - \exp\left[-\left(V / V_\eta\right)^\beta\right]\right\} \tag{2.4}$$

Formula (2.4) determines the time probability that the observed wind velocity V_{obs} is below the value V.

The Weibull distribution (2.4) is described by the two parameters β and V_η. For the value β data can be found in references ranging between 1,8 and 2,2. To assess the parameter V_η based on extreme value statistics $\beta = 2{,}0$ can be recommended. The probability that the observed wind velocity V_{obs} exceeds V is then:

$$P(V_{obs} > V) = \exp\left[-\left(V / V_\eta\right)^\beta\right] \tag{2.5}$$

Assuming V_T as the wind velocity having a two year return period: $V_T = V_{2a}$, the yearly probability is $3{,}42 \cdot 10^{-4}$ as explained above. The parameter V_η can be received from (2.5) with $\beta = 2{,}0$:

$$\exp\left[-\left(V_{2a} / V_\eta\right)^{2{,}0}\right] = 3{,}42 \cdot 10^{-4}$$

$$\left(V_{2a} / V_\eta\right) = \left[-\ln\left(3{,}42 \cdot 10^{-4}\right)\right]^{0{,}5}$$

$$V_\eta = V_{2a} / \left[- \ln \left(3{,}42 \cdot 10^{-4} \right) \right]^{0{,}5} = V_{2a} / 2{,}825 \tag{2.6}$$

2.3.3 Example

As an example, assuming that extreme value statistics show 20 m/s as having a two year return period, the formula (2.6) gives V_η = 7,1 m/s. During 63,2 % of the time the wind velocity will be below 7,1 m/s as can be seen from (2.4). In **Table 2.1** the yearly wind velocity distribution is given for this example.

Table 2.1 - Example for yearly wind velocity distribution based on the Weibull distribution (V_η = 7,1 m/s; β = 2,0)

Wind velocity m/s	Probability of		Duration of being exceeded in 1 year
	being exceeded	not being exceeded	
0,0	1,00	0,00	8760 h
2,5	0,88	0,12	7710 h
5,0	0,60	0,40	5260 h
7,5	0,32	0,68	2780 h
10,0	0,13	0,87	1140 h
12,5	0,04	0,96	360 h
15,0	0,01	0,99	90 h
20,0	0,0003	0,9997	2,5 h
25,0	$0{,}3 \cdot 10^{-5}$	~1,0	1,5 min

This example demonstrates how the distribution of the extreme values could be matched with the time distribution of wind speeds during the period of one year.

In [13] the following probability density function was found for wind velocity observations:

$$P\left(V_{obs} > V_\mathrm{T}\right) = 0{,}22 \exp\left(-0{,}045\, V_\mathrm{T}^{1{,}9}\right) \tag{2.7}$$

which represents also a Weibull distribution with β = 1,9 and V_η = 5,1 m/s demonstrating the suitability of the Weibull distribution for the purpose discussed.

2.3.4 Summary

To summarize the discussion, the time distribution of wind velocity at best should be taken directly from observations of weather stations. In cases where only statistics of the yearly extreme values or some values over a certain period are given, a Weibull distribution can be used to describe the time distribution of wind velocities during one year. The parameters of the Weibull distribution can be determined from distribution of annual maximum wind velocities by the procedure described within this clause.

2.4 Distribution of wind velocity depending on the height above ground level

The wind velocities vary with height above ground level and with wind span lengths. Due to the boundary effect, the wind velocities increase with the height above ground. There are two laws which are used in standards to describe the variation of the wind speed with the height.

To determine the mean wind velocity V_z at the height z above ground, the following potential law is often adopted:

$$V_z = V_R (z / z_R)^{\alpha}, \qquad (2.8)$$

where:

V_R reference mean wind velocity for the reference height z_R;
α roughness exponent depending on the terrain category A to D.

It should be mentioned that this law represents a statistical description of a series of measurements applying to the mean values at different heights. For a specific case the variation of instantaneous wind velocities, as well as of mean values over the height may differ from this law.

In the European Standard EN 50341-1 [8] and in CIGRE Technical Brochure No. 178 [10] the logarithmic law

$$V_z = V_R \cdot k_T \ln(z / z_0) \qquad (2.9)$$

is used to describe the variation of the wind velocity above ground level. Here is:

V_R reference mean wind velocity in terrain category B (II), 10 m above ground;
z height above ground;
z_0 roughness length;
k_T terrain factor. In terrain category B (II): $k_T = 1 / \ln(10/ z_0) = 1 / \ln(10/0,05) = 0,19$.

Values for k_T, z_0 and α are given in **Table 2.2** taken from the International Standard IEC 60826 [7] and the European Standard EN 50341-1 [8].

In paper [12] measurements of the wind profile in the terrain category B are reported. The measured mean values of roughness exponent α for terrain B varied between 0,16 and 0,21. It is expected that with increasing wind velocity the mean value of α tends to decrease. The results of the above mentioned paper seem to refer to values of the wind speeds characterized by return periods of 1 to 2 years.

Table 2.2 - Parameters for different terrain categories according to IEC 60826 and EN 50341-1

Terrain category IEC / EN	**Characteristics**	**Terrain factor k_T**	**Roughness length z_0 (m)**	**Roughness exponent α**	**Span coefficient k_L (2.12)**
A / I	Open sea, lakes with at least 5 km fetch upwind and smooth flat country without obstacles	0,16	0,01	0,10 to 0,12	0,073
B / II	Farm land with boundary hedges, occasional small farm structures, houses or trees	0,19	0,05	0,16	0,082
C / III	Suburban or industrial areas and permanent forests	0,22	0,30	0,22	0,098
D / IV	Urban areas in which at least 15 % of the surface is covered with buildings with mean height greater than 15 m	0,24	1,00	0,28	0,110

2.5 Wind loads on conductors

The wind load F_{WC} due to the effect of the wind pressure acting perpendicularly to the perpendicular direction upon a conductor having the wind span L_W is given by

$$F_{\mathrm{WC}} = n \cdot q_{\mathrm{z}} \cdot C_{\mathrm{xc}} \cdot G_{\mathrm{C}} \cdot G_{\mathrm{L}} \cdot d \cdot L_{\mathrm{W}}\,, \tag{2.10}$$

where

n	number of sub-conductors;
q_z	wind pressure corresponding to the mean wind velocity V_z at the height z above ground;
C_{xc}	drag coefficient of the conductor taken equal to 1,0 for the generally considered stranded conductors and wind velocities;
G_C	gust factor of the conductor which depends on the terrain category and the height above ground;
G_L	span factor as described in the following clause 2.6;
d	conductor diameter;
L_W	wind span. For wind action at insulator sets it is half of the span lengths of the adjacent spans.

The total effect of wind on bundle conductors can be taken as the sum of the actions on the *n* sub-conductors.

The mean wind pressure q_z in (2.10) is obtained from

$$q_z = (\rho / 2) \cdot V_z^2 \tag{2.11}$$

where

ρ is the air density corrected for temperature and altitude. The air density at a temperature of 15°C at sea level equals 1,225 kg/m^3;

V_z mean wind velocity at the height *z* above ground, see (2.8).

2.6 Variation of wind velocity along the span length

The wind does not act uniformly along the transmission line. Even within the section of a conductor which produces the wind load on an individual insulator set or an individual span the wind velocity varies considerably at a given time. The longer the wind span the more the wind velocity will vary along this span. This applies to the gust velocity as well as to the mean values of the wind velocities. Therefore, in general, the total wind load corresponding to a measured wind velocity does not increase to the same extent as the span length does. Relevant standards, e. g. EN 50341-1, take care of this effect by introducing a span factor G_L.

The International Standard IEC 60826 [7] contains data for the span factor describing the effect of the wind span lengths above 200 m. **Figure 2.2** shows the span factor for terrain category B.

The European Standard EN 50341-1 [8] specifies the span factor by the equation

$$G_L = 1{,}30 - k_L \ln(L_W), \tag{2.12}$$

where span coefficient k_L depends on the terrain category and L_W is the wind span in m. Table 2.2 contains data for span coefficient k_L. In Figure 2.2, the span factors are shown for terrain category B (II) depending on the wind span.

The German National Normative Annex EN 50341-3-4 [9] introduces a span factor G_L to take care of the effect of wind span lengths on wind loads which is calculated as:

$$G_L = 0{,}6 + 80 / L_W \tag{2.13}$$

The formula (2.13) is based on results gained on the Hornisgrinde test line [5]. For a wind span length of 600 m a span factor of 0,733 results from (2.13) which is considerably less than the span factor 0,907 resulting from IEC 60826 [7]. According to EN 50341-1, G_L = 0,775 results for a 600 m span which is closer to 0,733 than to 0,907.

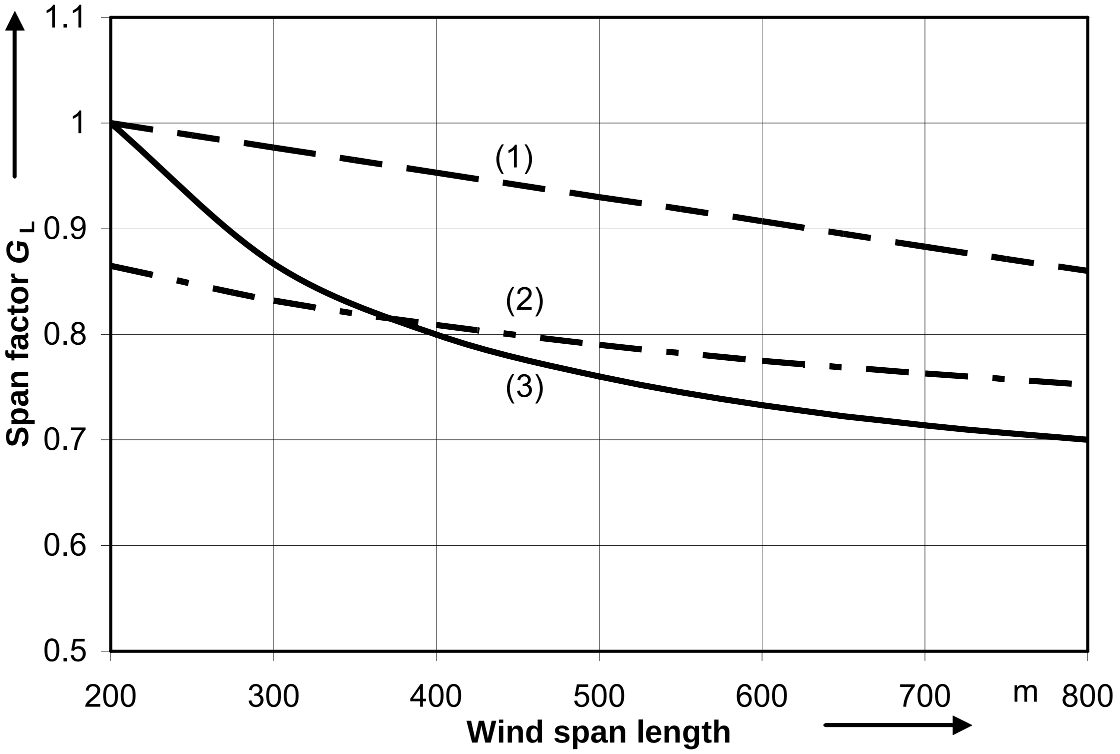

Figure 2.2 - *Span factor G_L (-) depending on the wind span length L_W (m)*
(1) IEC 60826; (2) EN 50341-1; (3) EN 50341-3-4

The effect of the differing procedures to take care of wind span length on the insulator swing angle can be demonstrated by an example. Supposing that for a ratio 1 for wind span to weight span a swing angle of 45° would result for a given wind speed and a wind span length of 200 m. Then for 600 m wind span the swing angle would be 42,2° based on the procedure of IEC 60826, 37,8° according to EN 50341-1 and only 36,2° according to EN 50341-3-4.

In order to calculate the insulator and conductor swing angle the effect of wind span lengths should be considered accordingly. The procedure given in IEC 60826 to take care of the span length seems to yield conservative results for the average swing angles especially under extreme wind conditions to which IEC 60826 applies.

Measurements in Hornisgrinde [5] verify the data obtained by the procedure stipulated in EN 50341-3-4 (See Clause 2.9.1).

However, for extreme swing angles and their corresponding loads, HQ [12] and EPRI experiments confirmed that the loads predicted by IEC 60826 can be exceeded in about 5 to 35% of the cases (See clause 2.9.2 and Table 2.3).

2.7 Calculation of swing angles of conductors and I-string insulators sets

2.7.1 Mean swing angles

The mean swing angle $ø_{\mathrm{ins}}$ of an insulator set may be related to the mean wind pressure by [1]:

$$\phi_{\mathrm{ins}} = \tan^{-1}\left[q_{\mathrm{z}} \frac{C_{\mathrm{xc}} \cdot G_{\mathrm{C}} \cdot G_{\mathrm{L}} \cdot d \cdot n \cdot L_{\mathrm{W}} + C_{\mathrm{xins}} \cdot A_{\mathrm{ins}} / 2}{m_C \cdot g \cdot n \cdot L_C + M_{\mathrm{ins}} \cdot g / 2} \right] \tag{2.14}$$

In this formula the following symbols are used:

q_{z}	mean wind pressure, see equation (2.11);
C_{xc}	drag coefficient of conductor;
G_{C}	gust factor of conductor;
G_{L}	span factor (see clause 2.6);
d	conductor diameter;
n	number of sub-conductors;
L_{W}	wind span of conductor;
C_{xins}	drag coefficient of insulator set, $C_{\mathrm{xins}} = 1{,}2$;
A_{ins}	insulator set area exposed to wind;
m_{C}	linear mass of conductor;
L_{C}	weight span of conductor;
g	gravitational acceleration, $g = 9{,}81\ \mathrm{m/s^2}$;
M_{ins}	mass of insulator set.

The term $m_{\mathrm{C}} \cdot g \cdot L_{\mathrm{C}}$ is the effective conductor weight taking into account the differences in the level of the conductor attachments at the adjacent towers.

The mean swing angle $ø_{\mathrm{C}}$ of a conductor in a horizontal span ($L_{\mathrm{C}} = L_{\mathrm{W}}$) can be obtained from:

$$\phi_C = \tan^{-1}\left[q_{\mathrm{z}} \cdot C_{\mathrm{xc}} \cdot G_{\mathrm{C}} \cdot G_{\mathrm{L}} \cdot d / \left(m_{\mathrm{C}} \cdot g \right) \right] \tag{2.15}$$

The parameters in (2.15) were explained in the context of equation (2.14).

In principle, formulae (2.14) and (2.15) were accepted in [5; 6; 12 and 13] and agreed upon within the Working Group SC B2, WG06, when discussing the Brochure No. 48 [4].

To establish the conductor positions and clearance under the action of wind the swing angles of insulator sets at the support and that of the conductors within the span are required.

The differences between individual published documents and between internal working group documents are due to the use of different reference wind velocities V_{R} and differing factors G_{C} and G_{L}.

The paper [11] and some internal working group documents use the 10 minute mean value for the calculation of the theoretical swing angle together with G_C and G_L equal to 1,00.

In the paper [12] formulae (2.14) and (2.15) are used as well for the calculation of the swing angles with 5 minute mean wind velocities. The factors G_C and G_L are 1,00, resulting in swing angles on the conservative side compared with the observations.

The paper [13] accepts the 10 minutes mean value for V_R and calculates the mean values of the swing angle ϕ for every given wind velocity using (2.14) and (2.15). The factors G_C and G_L are assumed to be 1,00.

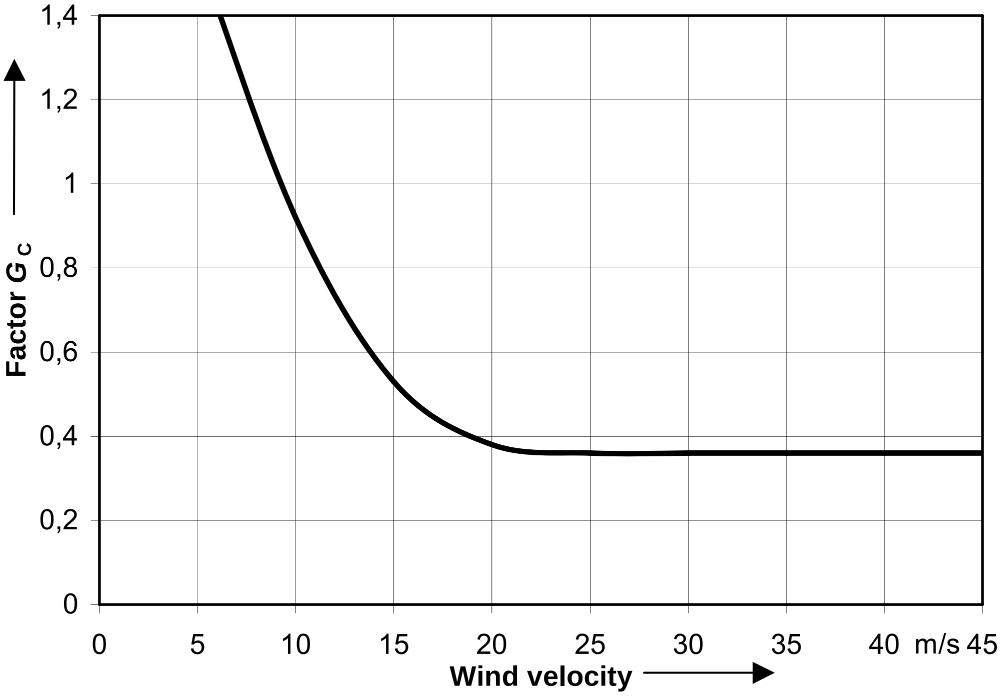

Figure 2.3 - *Combined wind factor for wind action on conductors*

A proposal from Australia takes V_R to be 10 second mean value multiplied by 0,9. A factor G_C is used which depends on the wind speed according to **Figure 2.3**. For wind speeds above 20 m/s the factor G_C is 0,36. G_L is taken as 1,00. From these considerations, it can be concluded that formulae (2.14) and (2.15) can be used for the determination of the swing angles. The parameters in (2.14) and (2.15) and the reference wind velocity V_R have to be selected accordingly on the basis of studies and experience.

2.7.2 Distribution of swing angles

In paper [13] additionally to the calculation of the mean swing angles according to (2.14) and (2.15), the distribution of the swing angles for a given mean value of the wind velocities is determined. While the mean values coincide with the results from formulae (2.14) and (2.15) there is a certain scattering due to the assumptions of varying wind velocities along the span. It is assumed that the actual swing angles for a given reference mean wind speed V_R are normally distributed with a mean value of $\bar{\phi}$ resulting from formulae (2.14) and (2.15) whereas the standard deviation σ_ϕ is given by:

$$\sigma_\phi = 2{,}25\left[1 - \exp\left(-V_R^2/230\right)\right] \text{ in (°)} \tag{2.16}$$

For small wind velocities σ_ϕ is zero and for large values it will be 2,25°. Assuming that the swing angles resulting from a given mean wind velocity V_R follow a Gaussian distribution (mean value $\bar{\phi}$ from formula (2.14) or (2.15) and standard deviation $\sigma_ø$ from formula (2.16), the paper [13] determines the time distribution of the swing angles *ø* by the following probability density function:

$$P(\phi) = \int_0^\infty P_\mathrm{V}(V)/\sigma_\phi(V)\cdot\sqrt{2\pi}\cdot\exp\left\{-\left[\left(\phi - \bar{\phi}(V)\right)/\sigma_\phi(V)\right]^2/2\right\}dV\,, \tag{2.17}$$

with $P_\mathrm{V}(V)$ according to equation (2.7), $\bar{\phi}(V)$ according to (2.14) or (2.15) and σ_ϕ according to (2.16).

Equation (2.17) yields the density for a given swing angle ϕ being exceeded. From an example the paper [13] concludes that consideration of a statistical distribution of the swing angles depending on wind velocities results in a lower time probability for a given swing angle being exceeded than without this procedure.

2.8 Effect of wind direction

Often wind statistics refer only to the occurrence of certain maximum wind velocity values without relating these wind velocities to certain wind directions. However, only winds acting perpendicularly to the line direction will cause the maximum swing angle. Therefore, statistics on wind directions would be necessary as well in order to establish realistic time probabilities for swing angles. As an approximation, based on contributions by members of the Working Group 06 of SC B2 it is proposed that the probability of the swing angle should be assumed as half of that of the corresponding wind velocity. This seems to be a fairly good guess for swing angles of more than 2°. For high probabilities of occurrence near 100%, e. g. small swing angles, this assumption might not be appropriate as far as the time probability is concerned.

2.9 Measurements of insulator swing angles

Various experimental investigations were carried out on test stands in the past to study the relation between wind velocities and swing angles, e. g. at Hornisgrinde [5] in Germany and [12] in Canada.

2.9.1 Measurements in Germany

The basic results of the experimental measurements in Hornisgrinde are:

- The swing angle observed for a measured wind velocity, whether instantaneous or average over a certain period of time, scatter considerably. **Figure 2.4** gives an example according to [5].

- The observed swing angles stay well below those determined theoretically using observed peak wind velocities and generally agreed formulae. In Figure 2.1 the difference is shown.

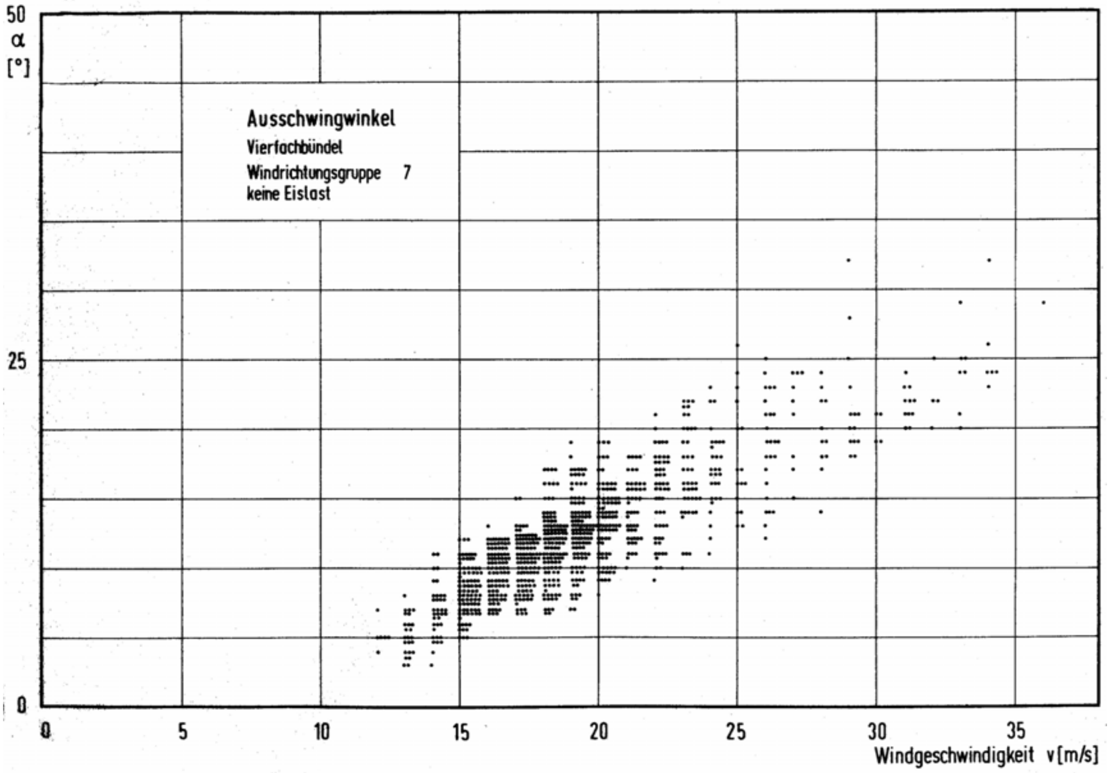

Figure 2.4 - *Recording of swing angles ø (°) (on vertical axis) for various wind velocities V (m/s) (on horizontal axis), conductor 4 ACSR 240/40, without ice [5]*

Therefore, in [6] the authors proposed to determine the swing angle on the basis of these test results. The test results were summarized in a diagram (**Figure 2.5**). The swing angle can be taken from Figure 2.5 for a given wind velocity and the parameter k_W, which is defined by:

$$k_W = \frac{d}{m_C} \cdot \frac{L_W}{L_C}, \tag{2.18}$$

where d is the conductor diameter in mm, L_W the wind span in m, L_C the weight span in m and m_C the linear mass of the conductor in kg/m.

As a reference the 1 minute velocity is used (see Figure 2.5). This procedure does not consider any effects of the span length.

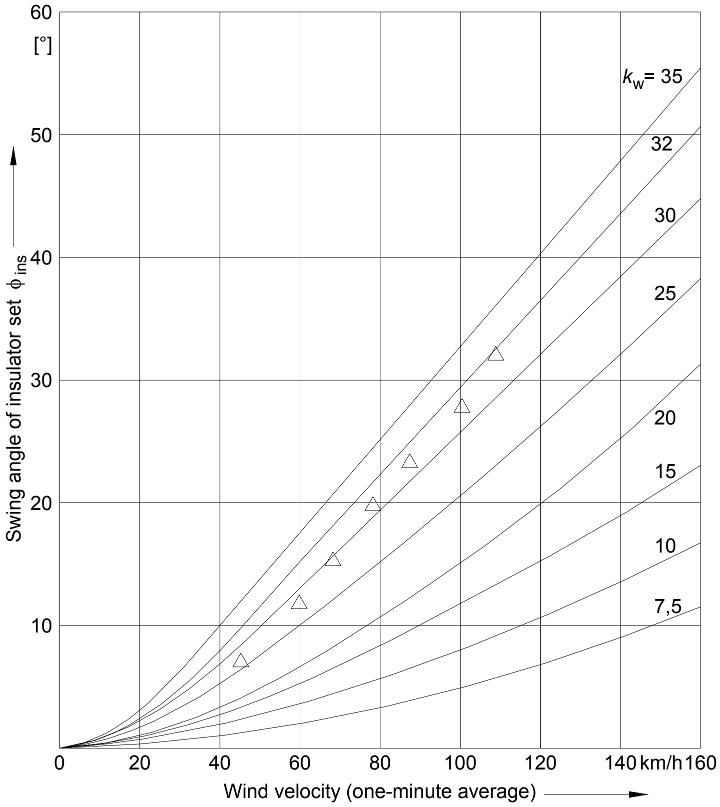

Figure 2.5 - *Determination of swing angles $ø_{ins}$ of insulator sets for various parameters k_w based on measurements [5; 6]. For instance, for a wind velocity V = 120 km/h and parameter k_w = 20, the swing angle of the insulator set, $ø_{ins}$ = 20°*

From Figure 2.5 a swing angle of 19° results for a wind velocity of 32 m/s (averaging period 1 minute) and a parameter k_W = 19. According to IEC 60826 [7] a wind velocity of 32 m/s related to an averaging period of 1 minute corresponds to a wind velocity of approximately 26 m/s with an averaging period of 10 minutes for terrain category C.

For formula (2.14) a swing angle of 38,2° results for 26 m/s with $G_C = G_L = 1$, which is nearly double the value according to Figure 2.5. Assuming a wind span of 400 m the span factor G_L according to formula (2.13) would be 0,8. Taking into account this factor a swing angle of 32° would result from (2.14).

In [13] two examples with 10 minute wind velocities of 18 m/s and 40 m/s are mentioned. The swing angles are 17° and 57°, respectively. Applying Figure 2.5 to these examples and converting the wind velocity to the one-minute value swing angles of 12° result for 18 m/s and 32° for 40 m/s, respectively. The procedure represented by Figure 2.5 gives considerably lower swing angles than all other procedures discussed.

Similar measurements on the swing angles of conductors alone are not known. However, it can be assumed that the same findings apply to the conductor swing angles as for insulator set swing angles since the main contribution to the latter is formed by the wind action on conductors.

2.9.2 Measurements in Canada

Measurements of the swing angle carried out in Canada are reported in paper [12]. The report contains diagrams and tables which depict the measured values over the swing angles calculated from formula (2.14) taking into account the 5 minute mean value of the wind velocity. **Figure 2.6** is typical of the data in [12].

It shows a scatter plot comparing measured and calculated angles for a 4 conductor bundle of Bersfort ACSR in a 320 m span. Other diagrams in this reference, for single conductors, show a very good agreement between calculated and measured swing angles while, for bundled conductors, the calculated angles are somewhat higher than those measured. The maximum measured angle is 17° which is fairly low compared with mean wind velocities of some 30 m/s which have to be expected during the life cycle of a transmission line.

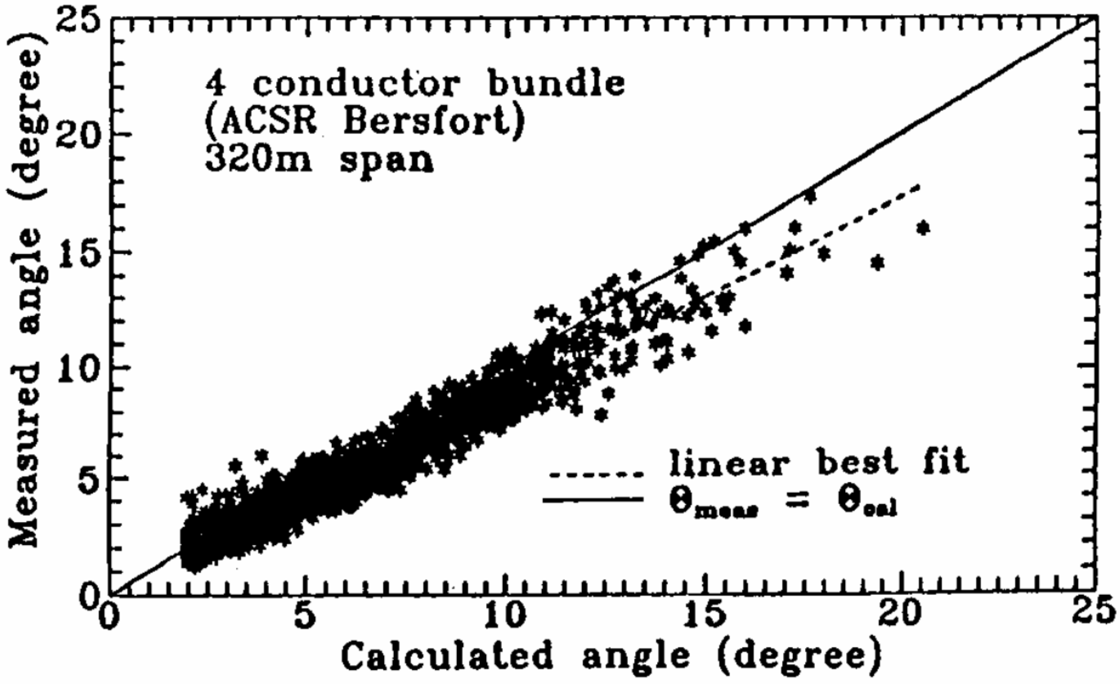

Figure 2.6 - *Measured versus calculated swing angles according to [12]*

In Figure 2.6 the “linear best fit” line is shown. This line yields to an angle of 18° for a calculated value of 21° for a 320 m span assuming the 5-minute mean wind velocity. Applying formula (2.14) with 10-minute mean wind velocity, which is approximately 5% less than the 5-minute mean for terrain type B, and a span factor $G_L = 0{,}96$ according to IEC 60826 (Figure 2.2) yields an angle of 18,5° which is equal to the best fit. Adopting formula (2.14) with 5 minute or 10 minute mean value as reference wind speed and a span factor G_L according to Figure 2.2 yields mean swing angles for insulator sets which agree well with measurements.

In **Table 2.3** mean values of the ratio of measured swing angles over the calculated ones and the corresponding standard deviations are shown. It can be recognized that on average the recorded swing angles were below those calculated. However, also swing angles were recorded which exceeded the calculated ones.

In fact, when measured, the swing angle will vary around the mean value. The maximum values will determine the maximum wind loads transferred by the conductor to the tower.

When one observes an overhead line under heavy winds, the insulators seem to be in a fixed swung position. However, the monitoring of swing angles by HQ [12]and EPRI by using sensitive equipment has confirmed that the swing angle varies around an average position or the apparent visual position, even within seconds. The maximum conductor wind loads transferred to structures were calculated in the HQ and EPRI tests from the swing angle value and the applied vertical loads. Table 2.3 confirms that swing angles using IEC 60826 equations are exceeded in 5 to 30% of all cases, even using actual line parameters. This percentage increases when general parameters suggested by IEC 60826 are used.

Table 2.3 - Ratio of measured over calculated mean swing angles of insulator strings (using actual parameters) according to [12]

Conductor configuration/ Measuring Period	**320 m span**			**411,5 m span**		
	Mean value	Standard deviation	Percentage of records exceeding calculated value	Mean value	Standard deviation	Percentage of records exceeding calculated value
4 ACAR 1300 Winter 1986-87	0,885	0,101	7,5	0,891	0,125	11,3
4 Bersimis Winter 1986-87	0,867	0,093	5,7	0,876	0,096	7,9
4 Bersfort Winter 1986-87	0,774	0,119	4,1	0,831	0,148	7,8
2 ACAR 588 Winter 1986-87	0,882	0,138	16,6	0,912	0,150	28,1
4 Bersfort Winter 1989-90	0,758	0,097	2,4	-	-	—
1 Bersfort Winter 1989-90	0,863	0,138	15,4	0,899	0,154	23,8

However, for the purpose of calculating clearances between conductors and tower parts, there is no need to consider the maximum peak of swing angle and an average of maximum swing angles may be sufficient. The distinction between maximum swing angle that generates the maximum transverse loads on the tower (and may cause its failure) and the average swing position during an extreme wind storm is quite important. The first case should be used for the design of structures, while the second value (average of extreme swing angles) could reasonably well be used for swing angle calculations.

2.10 Conclusion

To determine the distribution of swing angles it is necessary to establish the time distribution of wind velocities. For large wind velocities having a return period of more than two years the Gumbel distribution can be adopted which is based on the measured annual maximum wind velocities.

The most appropriate approach to establish a time distribution for relatively small wind velocities would be to evaluate the wind statistics from weather stations over the year and determine the time probability of certain wind speeds. However, the viability of such data would be limited to the area of the weather station. Alternatively, this time distribution can be established based on wind velocities with return periods of 1 to 2 years adopting a Weibull distribution, the parameters of which can be derived from wind velocities having a probability of occurrence of 1 or 2 years.

The mean swing angle of an insulator set under a given wind action can be reliably calculated based on the formula (2.14) using a mean wind speed averaged over 5 to 10 minutes with 5 minutes being a conservative value. The mean swing angle of a conductor is given by formula (2.15). The effect of wind span should be considered according to Figure 2.2. This approach yields realistic values for the mean values of the swing angles. It can be assumed for a certain wind action that the corresponding swing angles are normally distributed. Formula (2.16) gives an estimate for the standard deviation of swing angles.

Only winds acting perpendicularly to the line would cause the maximum swing angles. Since very often only the time distribution of wind velocities is known without reference to the wind direction the effect of wind direction the time probability of swing angles has to be determined by an approximation. In order to take care of the wind direction on the time probability of the swing angles can be assumed as being half of the corresponding wind velocities when the swing angle is more than 2°. The procedure described above enables establishing of a time distribution of swing angles of conductors and insulator sets. An example will be given in Part 5.

Part 3: Required clearances

3.1 Introduction

The tower top geometry has to be designed such that the probability of flashovers is kept to an acceptably low level. To achieve the design target:

- frequently occurring conductor positions, which result in still air and under light winds, will be combined with rare overvoltages due to lightning strokes or switching operations, and

- permanently present electric stresses under power frequency voltage with conductor positions having a low probability, which occur under high wind actions having return periods of 50 years and more.

Therefore, clearances in still air or under wind actions having a high probability of occurrence should be designed to withstand rare but possible voltage impulses which may occur after lightning strokes or during switching operations and clearances under extreme wind action should withstand the power frequency voltages.

There are various approaches available to determine the clearances necessary to withstand given electrical stresses under given environmental conditions. The aim of this Technical Brochure is not to establish new methods on this matter but to demonstrate how to apply well-known methods for the design of tower top geometry.

Between live parts of the insulators sets or conductors and earthed components and between conductors and earth wires minimum phase-to-earth clearances are required while between live conductors having differing phases minimum phase-to-phase clearances must be complied with.

3.2 Clearances in still air conditions

3.2.1 Clearances according to IEC 60071-1 and IEC 60071-2

The standards IEC 60071-1 [14] and IEC 60071-2 [15] deal only with phase-to-earth clearances. According to IEC 60071-1 the standard highest voltages for equipment are divided into two ranges:

- **Range 1:** above 1 kV to 245 kV included;
- **Range 2:** above 245 kV.

For lines within range 1 lightning impulses decide on the insulation level and for lines within range 2 switching impulses. There are several standard insulation levels associated with each of the rated highest voltage. **Table 3.1** lists some of the often used system voltage levels. The impulses are assumed to comply with the standard shapes as defined in IEC 60071-2, clause 3.18. Since the insulation is self-restoring the statistical withstand voltages are specified for which the probability of being withstood is 90% (see IEC 60071-1, clause 3.23). The coefficients of variation are assumed to be 3% for lightning impulses and 6% for switching impulses.

Table 3.1 - Coordination of impulse voltages and clearances

Voltage level		**Impulse voltages**			**IEC 60071-2**	**CIGRE Brochure 72**		**EN 50341-1**	
U_R	U_S	$U_{90\%\_ff}$	$U_{50\%\_ff}$	U_{max_sf}	D_{pe}	D_{pe}	D_{pp}	D_{pe}	D_{pp}
kV	**kV**	**kV**	**kV**	**kV**	**m**	**m**	**m**	**m**	**m**
110	123	450	490	-	0,9	0,94	0,96	0,89	1,00
		550	590	-	1,1	1,13	1,17	1,07	1,20
230	245	850	920	-	1,7	1,76	1,83	1,67	1,86
		950	1030	-	1,9	1,97	2,05	1,87	2,07
		1050	1140	-	2,4	2,18	2,26	2,05	2,29
400	420	1175	1270	850	2,4	2,40	2,70	2,25	2,67
		1300	1410	950	2,9	2,80	3,20	2,64	3,15
		1425	1540	1050	3,4	3,25	3,73	3,02	3,68
500	525	1300	1410	950	2,9	2,80	3,20	2,64	3,15
		1425	1540	1050	3,4	3,25	3,73	3,02	3,68
		1550	1680	1175	4,1	3,90	4,48	3,60	4,40

U_R	nominal voltage;
U_S	highest system voltage for equipment;
U_{ff}	fast front (lightning impulse) withstand voltage;
U_{max_sf}	maximum slow front (switching impulse) withstand voltage;
D_{pe}	minimum phase-to-earth clearance;
D_{pp}	minimum phase-to-phase clearance.

The minimum phase-to-earth clearances follow from IEC 60071-2, Tables VI A and IV B. They are listed in Table 3.1 as well. These clearances apply to standard reference conditions which are:

- Temperature 20°C;
- Air pressure 101,3 h Pa (1013 mbar);
- Humidity 11 g/m³.

They generally apply to altitudes not exceeding 1000 m. For differing conditions they have to be adjusted accordingly.

3.2.2 Clearances according to CIGRE Technical Brochure 72

The CIGRE Technical Brochure No. 72 [16] deals with the dielectric strength of external insulation and conductors, lightning and switching impulses. The lightning impulses to be used are that which can propagate beyond a few towers from the point of the lightning strike. For the purpose of determining clearances this is to be taken as $U_{50\%\_ff}$, i. e. the fast front (lightning) impulse voltage which results in 50%

withstands of a gap formed between the live parts and the tower or between conductors.

The slow front (switching) impulse voltage to be used is the highest that can occur on the lines called $U_{\mathrm{max\_sf}}$. There are means of limiting the switching surges, such as line entry surge arresters or pre-insertion resistors, in which case the appropriate $U_{\mathrm{max\_sf}}$ is the maximum value which can occur on the transmission lines. Unless means are taken to limit the switching surges, the possibility of reclosing on to a charged line has to be accommodated and in the absence of other information a truncated value of 3 p.u. should be assumed.

Table 3.2 - Gap factors k_g for slow-front overvoltages (1)

Configuration	k_g
Conductor-window, e. g. air gap configuration between a conductor inside a tower and the tower structure - vertical string or V string inside the window	1,25
Conductor-structure, e. g. air gap clearance between a conductor, connected to a free swinging insulator string at the extremity of a cross arm, and the tower structure - vertical string at the extremity of a cross arm - V-strings	1,45
Conductor-conductor	1,60

(1) The gap factor in this table are typical values only. In practice, other values supported by experiments may be used. Typical gap factor values can also be obtained from IEC 60071-2, annex G.

Phase-to-earth clearances

The corresponding phase-to-earth clearances $D_{\mathrm{pe\_ff}}$ and $D_{\mathrm{pe\_sf}}$ are calculated using the formulae (3.1) and (3.2):

Fast front overvoltages:

$$D_{\mathrm{pe\_ff}} = U_{50\%\_\mathrm{ff}} / \left[\left(0{,}74 + 0{,}26\, k_{\mathrm{g}} \right) \cdot 490 \right] \qquad (3.1)$$

Slow front overvoltages:

$$D_{\mathrm{pe\_sf}} = 2{,}17 \left\{ \exp\left[U_{\mathrm{max\_sf}} / \left(918 \cdot k_{\mathrm{a}} \cdot k_{\mathrm{g}} \right) \right] - 1 \right\} \qquad (3.2)$$

where:

$U_{50\%\_\mathrm{ff}}$ is the fast front (lightning impulse) overvoltage being withstood with 50% probability (kV);
$U_{\mathrm{max\_sf}}$ is the maximum slow front (switching) overvoltage which can occur on the transmission line (kV);
k_g is the gap factor (for slow front overvoltages see **Table 3.2**);
k_a is the altitude factor for altitude H:

$$k_{\mathrm{a}} = 1/\exp\left[\left(H/8150\right)^{\mathrm{m}}\right] \tag{3.3}$$

The exponent *m* follows from the CIGRE Technical Brochure No. 72 and is between 0,7 and 1,0.

Table 3.1 contains the results from equations (3.1) and (3.2) for altitude *H* = 0. The differences to IEC 60071-2 seem tolerable.

Phase-to phase clearances

The required phase-to-phase clearances $D_{\mathrm{pp\_ff}}$ and $D_{\mathrm{pp\_sf}}$ between conductors can be obtained modifying equations (3.2) and (3.3) as follows:

Fast front overvoltages

$$D_{\mathrm{pp\_ff}} = 1{,}2\,U_{50\%\mathrm{\_ff}} / \left[\left(0{,}74 + 0{,}26\,k_{\mathrm{g}}\right) \cdot 490\right] \tag{3.4}$$

Slow front overvoltages

$$D_{\mathrm{pp\_sf}} = 2{,}17\left\{\exp\left[1{,}4 \cdot U_{\mathrm{max\_sf}} / \left(918 \cdot k_{\mathrm{a}} \cdot k_{\mathrm{g}}\right)\right] - 1\right\}. \tag{3.5}$$

In equations (3.4) and (3.5) a gap factor k_{g} = 1,60 should be used to calculate the clearances between conductors.

3.2.3 Clearances according to EN 50341-1

In EN 50341-1 [8], Annex E, formulae for the calculation of the clearances D_{pe} and D_{pp} for slow front and fast front overvoltages are presented.

Phase-to-earth clearances

The required clearances to earthed components are:

Fast front overvoltages

$$D_{\mathrm{pe\_ff}} = U_{90\%\mathrm{\_ff}} / \left[530 \cdot k_{\mathrm{a}} \cdot k_{\mathrm{z\_ff}} \cdot \left(0{,}74 + 0{,}26\,k_{\mathrm{g}}\right)\right] \tag{3.6}$$

Slow front overvoltages

$$D_{\mathrm{pe\_sf}} = 2{,}17\left\{\exp\left[k_{cs} \cdot U_{\mathrm{max\_sf}} / \left(1080 \cdot k_{\mathrm{a}} \cdot k_{\mathrm{z\_sf}} \cdot k_{\mathrm{g}}\right)\right] - 1\right\}. \tag{3.7}$$

where:

$U_{90\%\_\mathrm{ff}}$ is the fast front overvoltage being withstood with 90% probability (kV): $U_{90\%\_\mathrm{ff}} = U_{50\%\_\mathrm{ff}} \cdot k_{\mathrm{z\_ff}}$;
$k_{\mathrm{z\_ff}}$ is the deviation factor of the fast front withstand voltage: $k_{\mathrm{z\_ff}}$ = 0,961;
$k_{\mathrm{z\_sf}}$ is the deviation factor of the slow front withstand voltage. For switching impulses: $k_{\mathrm{z\_sf}}$ = 0,922;
k_{a} is the altitude factor given in equation (3.3);

k_{cs} is the statistical coordination factor taken as 1,05.

The gap factor k_{g} depends on the type of gap (see Table 3.2). Default values are k_{g} = 1,25 to 1,30.

Phase-to-phase clearances

The required phase-to-phase clearances can be obtained from:

Fast front overvoltages

$$D_{\mathrm{pp\_ff}} = 1{,}2 \cdot U_{90\%\_\mathrm{ff}} / \left[530 \cdot k_{\mathrm{a}} \cdot k_{\mathrm{z\_ff}} \cdot \left(0{,}74 + 0{,}26\, k_{\mathrm{g}}\right)\right] \tag{3.8}$$

Slow front overvoltages

$$D_{\mathrm{pp\_sf}} = 2{,}17 \left\{\exp\left[1{,}4 \cdot k_{cs} \cdot U_{\mathrm{max\_sf}} / \left(1080 \cdot k_{\mathrm{a}} \cdot k_{\mathrm{z\_sf}} \cdot k_{\mathrm{g}}\right)\right] - 1\right\}. \tag{3.9}$$

In (3.8) and (3.9) k_{g} is the gap factor between conductors being assumed as 1,60.

3.3 Clearances under extreme wind conditions

3.3.1 Clearances according to CIGRE Technical Brochure 72

Under extreme insulator swing the clearances must be wide enough to withstand the power frequency voltage. For these conditions, no information is given in IEC 60071-2. The power frequency withstand voltage and the clearance $D_{\mathrm{pe\_pf}}$ can be expressed according to CIGRE Technical Brochure No. 72 [16] as follows.

Phase-to-earth clearances

The required clearance between phase and earth is:

$$D_{\mathrm{pe\_pf}} = \left[U_S / \left(350 \cdot k_\alpha \cdot k_{\mathrm{a}} \cdot k_{\mathrm{g\_pf}}\right)\right]^N \tag{3.10}$$

where:

U_{S} is the highest voltage for equipment (kV);

k_α takes care of the envisaged exclusion limit. The value k_α will be 0,88 for 10 % exclusion limit and 9% coefficient of variation;

k_{a} takes care of the altitude H. For k_{a} equation (3.3) can be used;

$k_{\mathrm{g\_pf}}$ is the gap factor depending on the geometry of the electrodes. The gap factor for power frequency voltages can be calculated based on the slow front by:

$$k_{\mathrm{g\_pf}} = 1{,}35\, k_{\mathrm{g}} - 0{,}35 \cdot k_{\mathrm{g}}^2 \tag{3.11}$$

The following default values may be assumed:

$k_{\mathrm{g\_pf}}$ = 1,25 for conductor to plane

k_{g_sf} = 1,40 for conductor to roofs, small objects
k_{g_sf} = 1,65 for conductor to conductor

For conductor to towers k_{g_pf} = 1,25 should be assumed.

N = 1 for $U_S \leq 400$ kV;
N = 1,67 for $U_S > 400$ kV.

Phase-to-phase clearances

The required clearance between conductors (phases) is:

$$D_{\mathrm{pp\_pf}} = \left[\sqrt{3} \cdot U_S / \left(350 \cdot k_\alpha \cdot k_\mathrm{a} \cdot k_{\mathrm{g\_pf}}\right)\right]^N \tag{3.12}$$

Between conductors k_{g_pf} = 1,65 can be set.

In **Table 3.3** the clearances under power frequency voltage are given.

Table 3.3: Clearances under power frequency voltage

Voltage level		CIGRE Brochure 72		EN 50341-1	
U_R	U_S	D_{pe_pf}	D_{pp_pf}	D_{pe_pf}	D_{pp_pf}
kV	kV	m	m	m	m
110	123	0,32	0,42	0,23	0,37
230	245	0,64	0,85	0,43	0,69
400	420	1,16	1,52	0,70	1,17
500	525	1,68	2,20	0,86	1,47

U_R	nominal voltage;
U_S	highest system voltage for equipment;
D_{pe_pf}	phase-to-earth clearance for power frequency voltages;
D_{pp_pf}	phase-to-phase clearance for power frequency voltages.

3.3.2 Clearances according to EN 50341-1

Phase-to-earth clearances

In EN 50341-1 [8], Annex E, formulae for the calculation of the clearances D_{pe_pf} between live and earth parts and for D_{pp_pf} for phase-to-phase clearances are given (see also [17]). Between live and earthed components it applies:

$$D_{\mathrm{pe\_pf}} = 1{,}64\left\{\exp\left[U_\mathrm{S} / \left(750 \cdot \sqrt{3} \cdot k_\mathrm{a} \cdot k_{\mathrm{z\_pf}} \cdot k_{\mathrm{g\_pf}}\right)\right] - 1\right\}^{0,.833} \tag{3.13}$$

where:

k_{z_pf} is the deviation factor being 0,910 for power frequency voltages;
k_{g_pf} is the power frequency factor, which can be obtained from equation (3.11).

Between earthed components and towers k_{g_pf} can be assumed as 1,25.

Phase-to-phase clearances

Between phases the clearances are obtained from:

$$D_{pp\_pf} = 1{,}64\left\{\exp\left[U_S / \left(750 \cdot k_a \cdot k_{z\_pf} \cdot k_{g\_pf}\right)\right] - 1\right\}^{0{,}833} \tag{3.14}$$

Between conductors the gap factor k_{g_pf} can be taken as 1,65.

In Table 3.3 the power frequency clearances are given.

The comparison with the data obtained from CIGRE Technical Brochure 72 reveals that the procedure according to EN 50341-1 results in less conservative data.

3.4 Summary

There are various approaches available to determine the clearances necessary to withstand given electrical stresses.

According to IEC 60071-1 the insulation level is determined by:

- fast front (lightning) impulse voltages U_{ff} for highest system voltages U_S above 1 kV to 245 kV included (Range I);
- slow front (switching) impulse voltages U_{sf} for highest system voltages U_S above 245 kV (Range II).

The standards IEC 60071-1 and IEC 60071-2 deal only with phase-to-earth clearances D_{pe}.

The formulae for phase-to-earth clearances D_{pe} and phase-to-phase clearances D_{pp} for slow and fast front overvoltages according to the CIGRE Technical Brochure No. 72 and EN 50341-1 are given in Clauses 3.2.2 and 3.2.3 and summarized in Table 3.1 for some of the often used system voltage levels U_S. The differences to IEC 60071-2 seem tolerable.

The formulae for the power frequency phase-to-earth clearances D_{pe_pf} and phase-to-phase clearances D_{pp_pf} according to the CIGRE Technical Brochure No. 72 and EN 50341-1 are given in Clauses 3.3.1 and 3.3.2 and summarized in Table 3.3. The comparison with the data obtained from CIGRE Technical Brochure 72 reveals that the procedure according to EN 50341-1 results in less conservative data. No information is given in IEC 60071-2.

Part 4: Coordination of conductor and insulator set positions and electrical stresses

Two conditions should be considered for the design of tower top geometry taken into account the varying position of conductors and insulator sets under the action of wind and the electrical stress of the air gap by power frequency voltages and overvoltages caused by lightning strokes or switching operations **(Table 4.1)**.

- The first condition is described by conductor and insulator positions which would occur under the action of the design wind velocities having a return period of say 50 years. These positions are combined with clearances required to withstand power frequency voltages. The flashover probability is that by which the design wind velocity will be exceeded.

- The second condition is described by conductor and insulator positions which are assumed as not being exceeded during 99 % of the time. These positions are combined with clearances required for the expected overvoltages caused by lightning strokes or switching operations. The flashover probability is that by which the design overvoltage conditions will be exceeded.

The above mentioned probabilities apply to standard reference conditions. For differing meteorological conditions they have to be adjusted accordingly.

Table 4.1 – Coordination of conductor positions and electrical stresses

Electrical stresses of the air gap		Conductor and insulator positions	
		Still air or moderate wind during 99% of time	High wind velocity with T = 50 years
	Probability	High	Low
Power frequency voltage	High	Covered by cases 1 & 2	Case 1
Lightning / switching impulse voltage	Low	Case 2	Not considered

To establish unfavourable mutual positions of two adjacent conductors, being live or earthed, in mid span it is assumed that the one of them is in a position given by the mean swing angle minus two standard deviations while the other would be in a position given by the mean swing angle plus two standard deviations. The application of this approach will be demonstrated by means of an example in Part 5.

Part 5: Example

5.1 Introduction

In this Part 5, the determination of tower top geometry and mid span clearances is demonstrated by means of an example for a suspension tower equipped with a twin conductor bundle 2 x Finch ACSR 564/72.

On the basis of the mean value of the yearly maximum wind velocities the following calculations are performed:

- The wind velocity for a given period using the Gumbel distribution function;
- The moderate wind velocity using the Weibull distribution function;
- The adjustment of the wind velocities to the time period and the height above ground;
- The mean swing angle of the suspension insulator set at tower;
- The mean swing angle of conductors at mid span;
- The scattering of the swing angle;
- The minimum electrical clearance;
- The horizontal distance between the attachment point and the tower body;
- The horizontal distance between the attachment points of two adjacent conductors in a horizontal configuration.

5.2 Data of the application example

The approach to determine tower top geometry and mid span clearances will be demonstrated by means of an example for a 400 kV suspension tower equipped with:

Conductors 2 x Finch ACSR 564/72;
Diameter d = 32,85 mm;
Linear mass m_C = 2,11 kg/m.

Mean conductor height above ground: z = 20 m;
Wind spans L_W = 400 m and 200 m; ratio wind to weight span: L_W / L_C = 1,0;
Mean value of yearly maximum wind velocities (height 10 m; 10 min mean value): $V_{10m/10\,min}$ = 20 m/s;
Coefficient of variation: $\sigma_V / \overline{V}$ = 0,14 (or standard deviation: σ_V = 2,8 m/s);
Terrain category B;
Mean suspension insulator length: l_{ins} = 5 m;
Mass of I-type insulator strings: M_{ins} = 300 kg;
Wind exposed area of insulating string: A_{ins} = 1,5 m²;
Drag coefficient of insulator set: C_{xins} = 1,2;
Highest system voltage: U_S = 420 kV;
Switching impulse voltage: U_{sf} = 1050 kV;
Number of sub-conductors: n = 2;
Distance between sub-conductors: b = 0,4 m;
Sag: f = 20 m.

5.3 Wind velocities

Equation (2.3) yields the wind velocities V_T corresponding to return periods from T = 2 to 50 years which are presented in **Table 5.1**.

Table 5.1 – Swing angles of insulator sets

Return Period *T* wind		Wind velocity V_T			Insulator swing angle ø				St. dev. angle	Probability wind (not) exceeded		Return Period or time %	
		Height / time			400 m span		200 m span						
		10 m	20 m	20 m	20 m	20 m	20 m	20 m					
		10min	5min	10min	5min	10min	5min	10min	σ_ϕ	$V > V_T$	$V < V_T$		
yr	days	m/s	m/s	m/s	°	°	°	°	°	%	%	year	%
50		27,3	32,0	30,5	42,2	39,4	42,0	41,6	2,22			100	
25		25,7	30,1	28,7	38,8	36,1	38,6	38,2	2,21			50	
10		23,7	27,8	26,5	34,4	31,8	34,2	33,8	2,17			20	
5		22,0	25,8	24,6	30,5	28,1	30,4	30,0	2,13			10	
2	730	19,5	22,9	21,8	24,8	22,8	24,7	24,4	2,02	0,0342	99,97	4	
	250	18,2	21,3	20,3	22,0	20,1	21,8	21,5	1,94	0,100	99,90		0,050
	100	16,9	19,8	18,9	19,2	17,5	19,1	18,8	1,84	0,25	99,75		0,125
	50	15,9	18,7	17,8	17,1	15,6	17,0	16,8	1,75	0,5	99,5		0,25
	25	14,8	17,4	16,5	14,9	13,6	14,8	14,6	1,64	1	99		0,5
	12,5	13,7	16,1	15,3	12,9	11,7	12,8	12,6	1,52	2	98		1,0
	5,0	12,0	14,1	13,4	9,9	9,0	9,9	9,7	1,30	5	95		2,5
	2,5	10,5	12,3	11,7	7,6	6,9	7,6	7,5	1,09	10	90		5,0
	1,25	8,8	10,3	9,8	5,4	4,9	5,4	5,3	0,83	20	80		10
	0,50	5,8	6,8	6,5	2,3	2,1	2,3	2,3	0,41	50	50		25
		3,3	3,9	3,7	0,8	0,7	0,8	0,7	0,14	80	20		40
		2,2	2,6	2,5	0,3	0,3	0,3	0,3	0,06	90	10		45
		1,6	1,9	1,8	0,2	0,2	0,2	0,2	0,03	95	5		47,5
		0,7	0,8	0,8	0,0	0,0	0,0	0,0	0,01	99	1		49,5
		0,2	0,2	0,2	0,0	0,0	0,0	0,0	0,00	99,9	0,1		50

The wind velocity which will be exceeded during a given probability *P* of the year can be determined from (2.5) with $\beta = 2{,}0$.

$$V = V_\eta \cdot \sqrt{-\ln(P)} \tag{5.1}$$

The parameter v_η of the Weibull distribution is then calculated from (2.6) based on the wind velocity having a return period of two years which is 19,5 m/s.

$$V_\eta = 19{,}5 / 2{,}825 = 6{,}92 \text{ m/s}$$

The wind velocity 19,5 m/s will be exceeded during $3{,}42 \cdot 10^{-2}$ % of one year according to equation (2.5).

5.4 Mean swing angles of insulator sets

Table 5.1 also lists the mean insulator swing angles for the various wind velocities.

The 5 min wind velocity 20 m above ground is calculated from (2.8) and IEC 60826 Annex A.4.

$$V_{20\,\mathrm{m/5\,min}} = V_{10\,\mathrm{m/10\,min}} \cdot \left(\frac{20}{10}\right)^{0{,}16} \cdot 1{,}05 = V_{10\,\mathrm{m/10\,min}} \cdot 1{,}173 \tag{5.2}$$

The mean swing angle of insulator sets follows from equation (2.14) and for conductors from equation (2.15). The span factor G_L is taken from Figure 2.2 to be 0,96 for 400 m wind span following the IEC 60826 graphs (Figure 2.2). A span factor G_L = 0,8 would result for DIN EN 50341-3-4. Air density ρ is taken to be 1,225 kg/m². For 200 m wind span G_L = 1,0.

For the 50 year return period wind $V_{20\mathrm{m/5min}}$ = 32,0 m/s a swing angle of 42,2° results from (2.14). Assuming G_L = 0,8 the swing angle would be reduced to 38,7°, representing a reduction of approximately 8%.

Alternatively, the mean swing angles are determined for the 10 min wind 20 m above ground:

$$V_{20\,\mathrm{m/10\,min}} = V_{10\,\mathrm{m/10\,min}} \cdot \left(\frac{20}{10}\right)^{0{,}16} = V_{10\,\mathrm{m/10\,min}} \cdot 1{,}117 \tag{5.3}$$

For the wind velocity $V_{20\mathrm{m/10min}}$ = 30,5 m/s a swing angle of 39,4° is obtained, which is approximately 7% less than for the 5 min wind. Assuming a 200 m wind span the swing angles would be 42,0° and 41,6°, respectively being nearly the same values as for a 400 m wind span.

To determine the swing angle from Figure 2.5 the factor k_W is established to be k_W = (32,85 / 2,11) · (400 /400) = 15,6.

For $V_{20\mathrm{m/5\,min}}$ = 32,0 m/s, the one minute wind speed follows from IEC 60826 to be 32,0 · 1,16 / 1,05 = 35,4 m/s ≅ 120 km/h. Figure 2.5 yields a swing angle of approximately 20° which is considerably less than the values gained from (2.14) irrespective of wind span length and averaging period of wind velocities.

The procedure does not take into account the angle of attack of the wind to the conductor direction. Following clause 2.8 it is assumed that the probability of occurrence of swing angles above approximately 2° is only half of that of the corresponding wind velocity. In the example swing angles of 2,3° and more would then occur during 25% of the year and swing angles of more than 11,7° to 12,9° only during 1% of the year. During 75% of the year the insulator swing angles are less than ~2,3°.

For design of the tower top geometry swing angles having a probability of occurrence of 1% or more during a year should be combined with the distance necessary to withstand switching or lightning surges, and the swing angle under wind load according to design wind velocity return period should be combined with the distance to withstand power frequency.

5.5 Scattering of swing angles of insulator sets

To take care of the scattering of swing angles ø under a given wind velocity formula (2.16) is used. For V_R = 32,0 m a standard deviation σ_ϕ of 2,22° results. The standard deviations σ_ϕ are listed in Table 5.1. **Figure 5.1** shows the swing angle depending of the wind velocity.

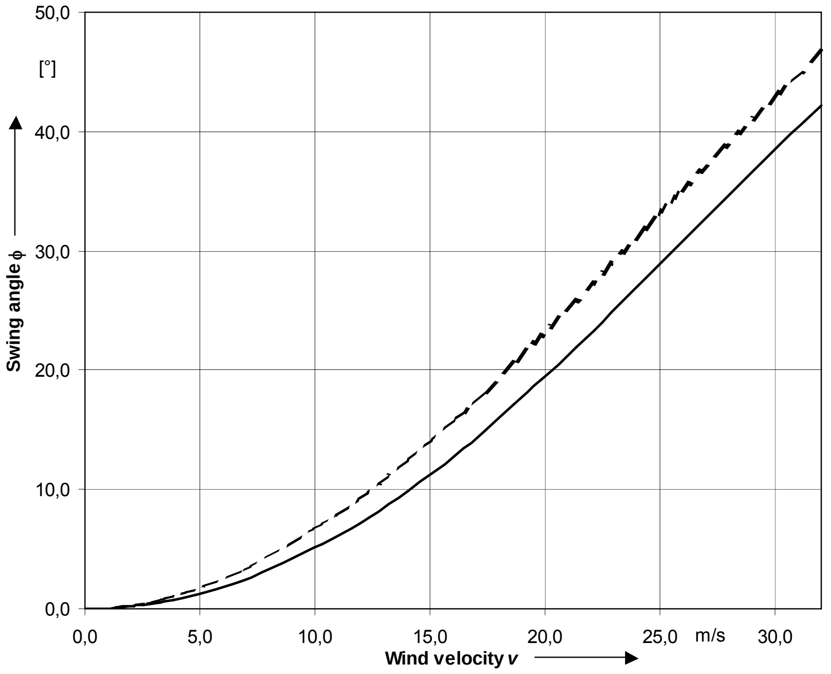

Figure 5.1 - *Mean insulator set swing angle and extreme swing angle (mean value plus two standard deviations, broken line) on depending wind velocity for twin bundle ASCR Finch*

To determine an unfavourable conductor position, an extreme swing angle of $(\bar{\phi}+2\sigma_\phi)$ is assumed, which is 42,2° + 2 · 2,2° = 46,6° for the 400 m wind span and 5 min wind velocity and 39,4° + 2 · 2,2° = 43,8° for 400 m wind span and 10 min wind velocity.

For the swing to be expected during 1% of the year (corresponding to 16,1 m/s and 15,3 m/s, respectively according to Table 5.1) a standard deviation of σ_ϕ = 1,5° results. Then the swing angles to be considered under this condition are 12,9° + 2 · 1,5° = 15,9° and 11,7° + 2 · 1,5° = 14,7°.

Under low wind conditions, the 400 m wind span with 5 min wind velocities leads to a distance of 4,97 m between the insulator attachment and the tower structure. The 400 m wind span combined with 10 min wind velocity yields a distance of 4,87 m. Under high wind conditions, the 400 m wind span with 5 min wind velocities leads to a distance of 4,99 m between the insulator attachment and the tower structure. The 400 m wind span combined with 10 min wind yields a distance of 4,82 m. Only under high wind conditions, there would be a considerable effect of the averaging period of wind.

Figure 5.2 depicts the results of this exercise. Position 1 is combined with the power frequency voltage (see Table 3.3) and position 2 with the switching impulse withstand voltage (see Table 3.1). For this example both conditions yield approximately the same distance between earthed structure and conductor attachment, however, the maximum swing angles combined with clearances for power frequency voltages govern the tower top geometry.

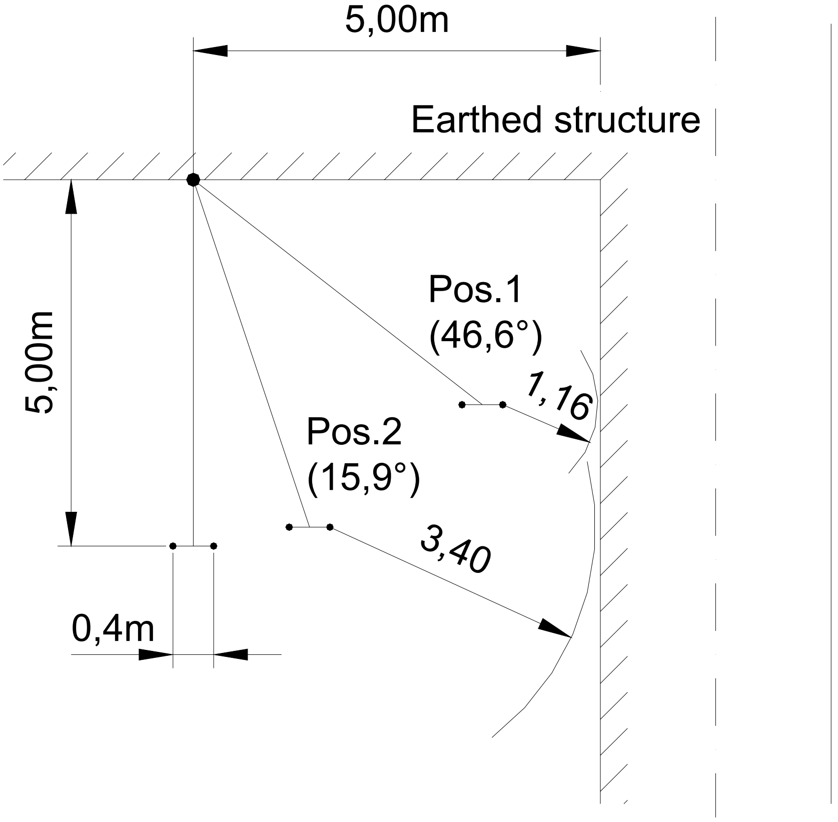

Figure 5.2 - *Example for clearance between insulator set and earthed structure (400 kV, twin bundle ACSR Finch, 5 min wind velocity, 400 m wind span)*

The results regarding the clearances between the insulator set and the earthed structure for this exercise are summarised in **Table 5.2** below.

Table 5.2 - Clearances between insulator set and earthed structure

Position		**Wind**		**Insulator swing angle**			**Clearance**		
No.	**Wind condition**	**Period**	**Wind speed**	**Mean swing angle**	**Standard deviation**	**Max. swing angle**	**Impulse voltage**	**Power frequency voltage**	**Distance to earth**
			$V_{20\,m}$	ø	σ_ϕ	ø+2σ_ϕ	D_{pe}	D_{pe_pf}	L_0
							IEC	TB 72	
		min	m/s	°	°	°	m	m	m
1	High: T = 50 years	5	32,0	42,2	2,2	46,6	-	1,16	4,99
		10	30,5	39,4	2,2	43,8			4,82
2	Low swing 1% of year	5	16,1	12,9	1,5	15,9	3,40	-	4,97
		10	15,3	11,7	1,5	14,7			4,87

5.6 Swing angles of adjacent conductors

Table 5.3 lists the mean **conductor swing angles** for the various wind velocities. For the 50 year return period wind an angle of 43,7° results from (2.15) for the 5 min wind. Assuming G_L = 0,8 the swing angle would be reduced to 40,0°, representing a reduction of approximately 8%.

Table 5.3: Swing angles of conductors

Return Period T wind		Wind velocity V_T			Insulator swing angle ø				St. dev. angle	Probability wind (not) exceeded		Return Period or time %	
		Height/time			400 m span		200 m span						
		10m	20m	20m	20m	20m	20m	20m					
		10min	5min	10min	5min	10min	5min	10min	σ_ϕ	V> V_T	V< V_T		
yr	days	m/s	m/s	m/s	°	°	°	°	°	%	%	year	%
50		27,3	32,0	30,5	43,7	40,9	44,9	42,1	2,22			100	
25		25,7	30,1	28,7	40,2	37,5	41,5	38,7	2,21			50	
10		23,7	27,8	26,5	35,7	33,1	36,9	34,3	2,17			20	
5		22,0	25,8	24,6	31,8	29,4	32,9	30,4	2,13			10	
2	730	19,5	22,9	21,8	26,0	23,8	27,0	24,8	2,02	0,0342	99,97	4	
	250	18,2	21,3	20,3	23,0	21,0	23,9	21,9	1,94	0,100	99,90		0,05
	100	16,9	19,8	18,9	20,1	18,4	20,9	19,1	1,84	0,25	99,75		0,125
	50	15,9	18,7	17,8	17,9	16,4	18,7	17,0	1,75	0,5	99,5		0,25
	25	14,8	17,4	16,5	15,7	14,3	16,3	14,9	1,64	1	99		0,5
	12.5	13,7	16,1	15,3	13,5	12,3	14,1	12,8	1,52	2	98		1,0
	5,0	12,0	14,1	13,4	10,5	9,5	10,9	9,9	1,30	5	95		2,5
	2,5	10,5	12,3	11,7	8,0	7,3	8,4	7,6	1,09	10	90		5,0
	1,25	8,8	10,3	9,8	5,7	5,1	5,9	5,4	0,83	20	80		10
	0,50	5,8	6,8	6,5	2,5	2,2	2,6	2,3	0,41	50	50		25
		3,3	3,9	3,7	0,8	0,7	0,8	0,8	0,14	80	20		40
		2,2	2,6	2,5	0,4	0,3	0,4	0,3	0,06	90	10		45
		1,6	1,9	1,8	0,2	0,2	0,2	0,2	0,03	95	5		47,5
		0,7	0,8	0,8	0,0	0,0	0,0	0,0	0,01	99	1		49,5
		0,2	0,2	0,2	0,0	0,0	0,0	0,0	0,00	99,9	0,1		50

For the 10 min wind velocity an angle of 40,9° is obtained, which is approximately 7% less than for the 5 min wind. Assuming a 200 m wind span the swing angles would be 44,9° and 42,1°, respectively being a little more than the values for a 400 m wind span.

To determine an unfavourable conductor position, an extreme swing angle of $(\bar{\phi} + 2\sigma_{\phi})$ is assumed, which is 43,7° + 2 · 2,2° = 48,1° for the 400 m wind span and 5 min wind velocity and 40,9° + 2 · 2,2° = 45,3° for 400 m wind span and 10 min wind velocity. The swing angle of the adjacent conductor is $(\bar{\phi} - 2\sigma_{\phi})$ being 43,7° - 2 · 2,2° = 39,3° for the 400 m wind span.

For the swing to be expected during 1% of the year (corresponding to 16,1 m/s and 15,3 m/s, respectively) a standard deviation of σ_ϕ = 1,5° results. Then the swing angles to be considered under this condition are 13,5° + 2 · 1,5° = 16,5° and 12,3° + 2 · 1,5° = 15,3°. The swing angle of the adjacent conductor is $(\bar{\phi} - 2\sigma_{\phi})$ being 13,5° - 2 · 1,5° = 10,5° for the 400 m wind span.

5.7 Mid span clearances

Figure 5.3 depicts the results of the exercise regarding the mid span clearances. The high wind swing angles are combined with the clearance for power frequency voltages (see Table 3.3) and the low wind or still air condition with the switching impulse withstand voltage (see Table 3.1). For this example low wind condition governs the required spacing. A spacing of 6,70 m is required at the tower to achieve the necessary clearance at mid span.

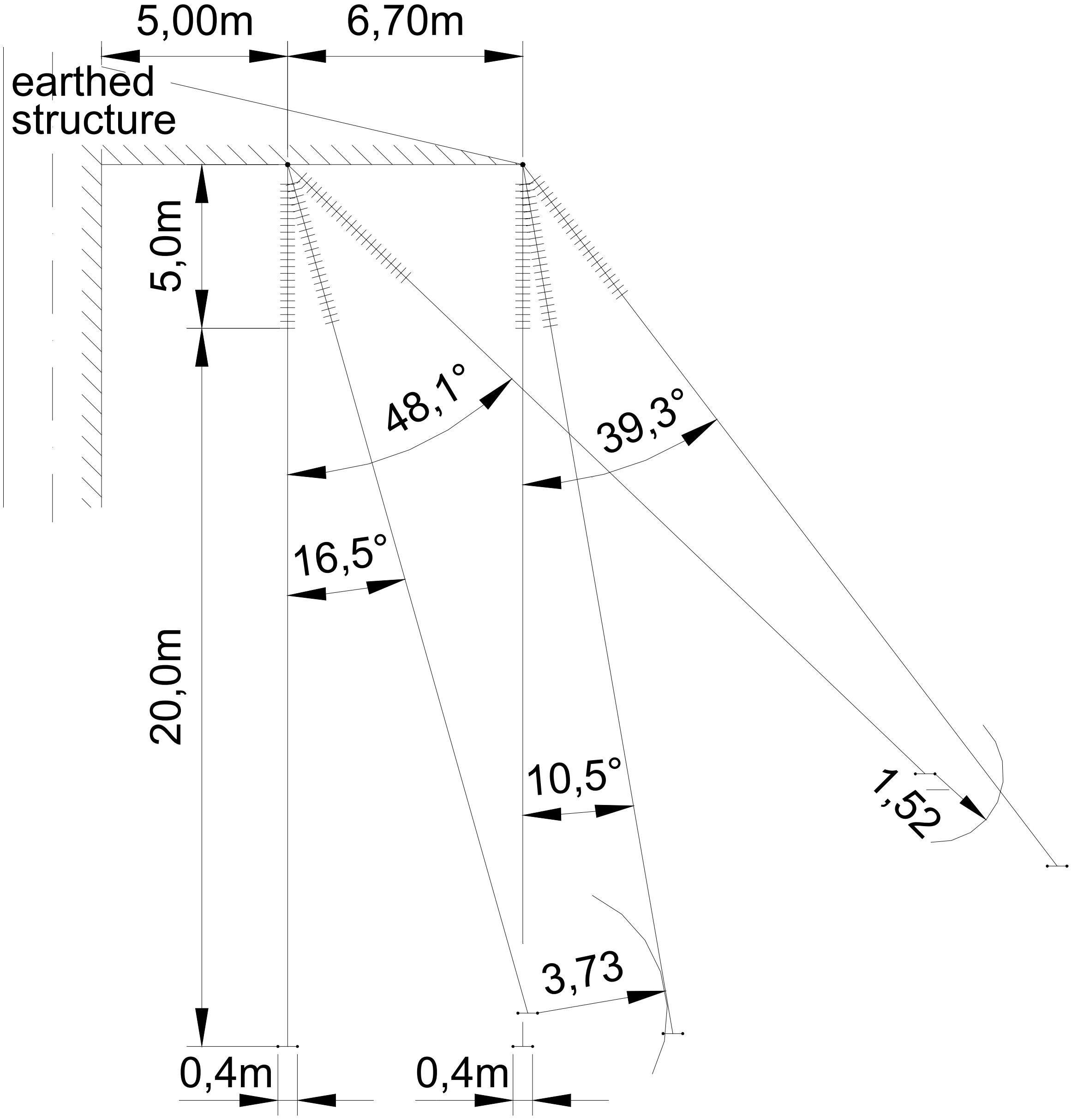

Figure 5.3 - *Clearances between adjacent conductors in mid span*

The results regarding the clearances between the adjacent conductors for this exercise are summarised in **Table 5.4** below.

Table 5.4 - Clearances between adjacent conductors in mid span

Position		Wind		Conductor swing angle				Clearance TB 72		
No.	Wind condition	Period	Wind speed	Mean swing angle	Stand. Dev.	Min. swing angle	Max. swing angle	Impulse voltage	Power freq. voltage	Dist. cond
			$V_{20\ m}$	ø	σ_ϕ	ø $-2\sigma_\phi$	ø$+2\sigma_\phi$	D_{pp}	D_{pp_pf}	L_1
		min	m/s	°	°	°	°	m	m	m
1	High: T = 50 years	5	32,0	43,7	2,2	39,3	48,1	-	1,52	-
		10	30,5	40,9	2,2	36,5	45,3			
2	Low Swing 1% of years	5	16,1	13,5	1,5	10,5	16,5	3,73	-	6,70
		10	15,3	12,3	1,5	9,3	15,3			

5.8 Formulae for the tower top geometry

The formulae for the calculation of the horizontal distances:

- L_0 between the first conductor attachment point and the tower structure;
- L_1 between the conductor attachment points on the same cross-arm,

are given below:

$$L_0 = D + l_{ins} \cdot \sin ø_{max} + b/2 \tag{5.4}$$
$$L_1 = L_h + (D^2 - L_v^2)^{1/2} + b;\ L_1 = 0 \text{ if } D \le L_v \tag{5.5}$$

with:

$$L_h = (f + l_{ins})(\sin ø_{max} - \sin ø_{min}) \tag{5.6}$$
$$L_v = (f + l_{ins})(\cos ø_{min} - \cos ø_{max}) \tag{5.7}$$

where:

D	Minimum clearance: D_{pe} for phase-to-earth clearance and D_{pp} for phase-to-phase clearance;
f	Sag of conductor;
l_{ins}	Mean length of suspension insulator set;
ø	Insulator swing angle for L_0 (5.4) and conductor swing angle for L_1 (5.5);
b	Outside diameter of the conductor bundle.

For still air we obtain (400 m wind span and 5 min wind velocity):

$L_0 = 3{,}40 + 5 \cdot \sin 15{,}9° + 0{,}2 = 4{,}97$ m
$L_1 = 25 \cdot (\sin 16{,}5° - \sin 10{,}5°) + \{3{,}73^2 - [25 \cdot (\cos 10{,}5° - \cos 16{,}5°)]^2\}^{1/2} + 0{,}4 = 6{,}7$ m

For high wind we obtain (400 m wind span and 5 min wind velocity):

$L_0 = 1{,}16 + 5 \cdot \sin 46{,}6° + 0{,}2 = 4{,}99$ m

L_1 = 0 as $D - L_v$ = 1,52 – 25 · (cos 39,3° - cos 48,1°) < 0 m

5.9 Comparison with an empirical approach

For comparison, the tower top geometry according to EN 50341-3-4 [9] was established as well. Under this assumption the swing angle to be considered for the tower top geometry would be 31,2° which has to be combined with a clearance of 2,10 m resulting in a distance of 5,00 m between tower structure and insulator attachment (Figure 5.3). The minimum clearance between adjacent conductors is obtained from:

$$c_{\min} = 0{,}6\sqrt{f + l_{ins}} + K \cdot D_{pp} + b \qquad (1.1)$$

With conductor sag f = 20 m, mean insulator length l_{ins} = 5 m, distance between sub-conductors b = 0,4 m; coefficient K = 0,75 and phase-to-phase clearance D_{pp} = 3,2 m it is obtained $c_{\min}$ = 5,80 m from (1.1). In **Figure 5.4** the results are presented.

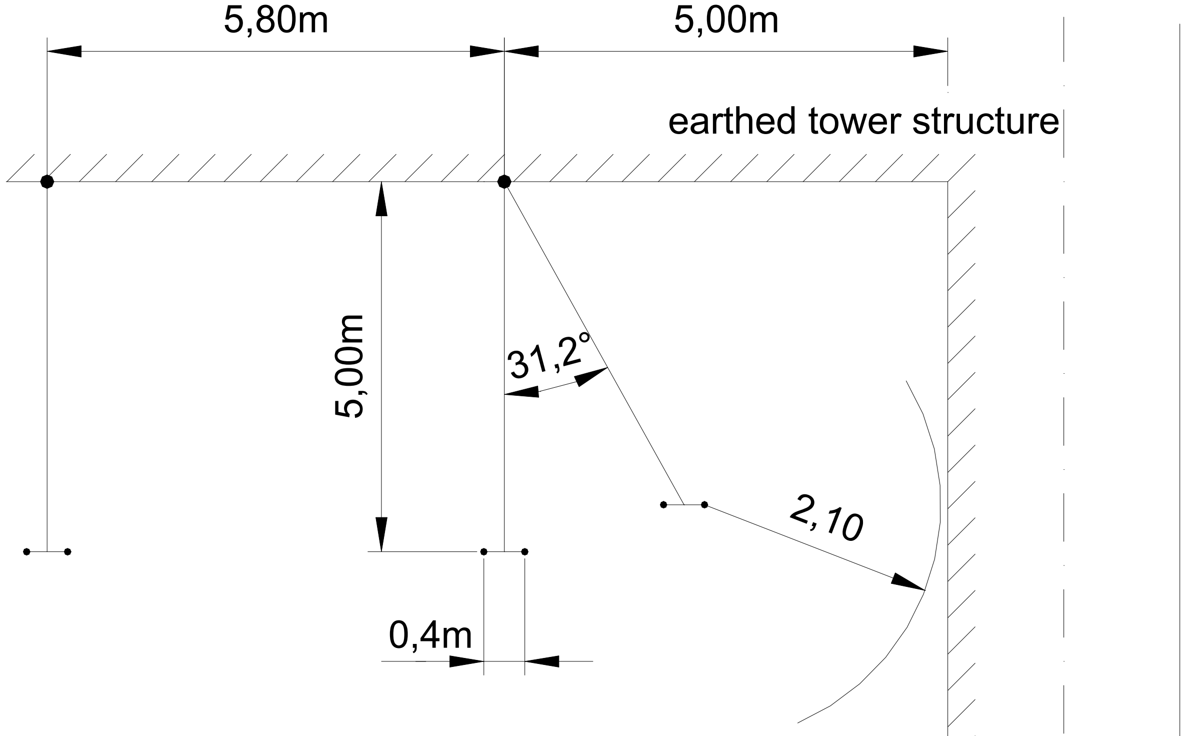

Figure 5.4 - *Tower top geometry according to EN 50341-3-4*

5.10 Summary

The design of the tower top is performed in 5 steps.

- The wind velocities for two cases are calculated:
  - A wind velocity with a return period of 50 years using the Gumbel distribution function for extreme values;
  - A moderate wind velocity using the Weibull distribution function;

- The wind velocities are adjusted to the time period and the height above ground according to the IEC 60826 equations. In Tables 5.1 and 5.3 the results are given for a 5 minute wind speed 20 m above ground level;

- The mean swing angle for the ratio wind load to conductor weight is calculated. The results are somewhat different for the swing angle of:
  - the suspension insulator set at tower;
  - the conductors at mid span.

- Further the scattering of the swing angle is determined. For this example two times the standard deviation has been considered.
  - The maximum swing angle at tower is obtained by adding two standard deviations to the mean swing angle of the insulator set. The maximum angle for the two positions at tower are depictured in Figure 5.2;
  - For the adjacent conductors both the minimum and maximum swing angles are obtained respectively by deducing and adding two standard deviations. The most unfavourable positions of the swinging conductors are depictured in Figure 5.3.

- Finally the minimum electrical clearance taken from Tables 5.2 and 5.4 are used to determine the horizontal distance between:
  - The attachment point of the first conductor and the tower structure (5,0 m in Figure 5.2);
  - The attachment points of two adjacent conductors in horizontal configuration (6,7 m in Figure 5.3).

The numerical results of the calculations are summarized in Tables 5.1-5.2 and Figure 5.2 for the clearances between insulator set and earthed structure at tower; in Tables 5.3-5.4 and Figure 5.3 for clearances between adjacent conductors in mid span.

Finally, a comparison has been made with the empirical equation (1.1) from Part 1 (Figure 5.4).

The application example covers two cases or positions – high wind and moderate wind velocities - when designing tower top geometry and mid span clearances.

Reference wind speeds and ice loads as well as the number of standard deviations for scattering have to be selected accordingly on the basis of studies and experience.

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Appendix A – Answers to the Questionnaire on Mid Span Clearances

A.1 - Answers to Questions 1 to 7

Question		**1.Meth.**		**2. Clearance**				**3. Load case**			**4.Withst.**		**5.**	**6. Mech**		**7. Elect**	
Country		**Compulsory national standard, law**	**Other design methods**	**Direct value**	**Empirical equation**	**Probabilistic method**	**Other method**	**Deterministic method**	**Simplified probabilistic**	**Probabilistic method**	**Withstand voltage in standard**	**Probabilistic method**	**Table of overvoltages**	**More than 1 mech. reliability level**	**Relevant for mid span clearances**	**More than 1 electr. reliability level**	**Relevant for mid span clearances**
(1)		**1a**	**1b**	**2a**	**2b**	**2c**	**2d**	**3a**	**3b**	**3c**	**4a**	**4b**	**5**	**6a**	**6b**	**7a**	**7b**
1	AU	Y	N	N	Y	N	-	N	N	N	N	N	-	N	-	N	N
2	BE	Y	N	N	Y	N	N	Y	N	N	N	N	X	N	N	N	N
3	BR	Y	Y	Y	-	N	N	-	-	-	Y	Y	X	Y	N	Y	N
4	CZ	Y	Y	N	Y	N	N	Y	N	N	Y	Y	X	Y	N	Y	N
5	DE	Y	N	N	Y	N	N	N	Y	N	N	N	X	N	N	N	N
6	FI	Y	Y	N	Y	N	N	Y	-	-	Y	-	X	N	-	N	N
7	FR	Y	N	Y	N	N	N	Y	N	N	Y	N	-	N	-	Y	N
8	GB	N	Y	N	Y	N	-	Y	N	N	N	N	-	Y	N	N	N
9	IT	Y	N	N	Y	N	N	N	N	N	N	N	X	Y	N	N	N
10	JP	Y	Y	N	Y	Y	Y	N	N	Y	Y	Y	X	Y	N	Y	N
11	LT	Y	N	Y	N	N	N	-	N	N	N	N	X	N	N	N	N
12	NL	Y	N	N	Y	N	N	Y	N	N	Y	N	X	N	N	Y	N
13	NO	Y	Y	Y	Y	N	Y	Y	N	N	Y	N	-	N	-	N	N
14	NZ	Y	Y	N	Y	N	N	Y	N	N	Y	N	X	Y	N	Y	N
15	RS	Y	Y	N	Y	-	-	Y	-	-	Y	N	X	N	-	N	N
16	UA	Y	N	Y	Y	N	N	Y	N	N	N	N	-	Y	N	N	N
17	ZA	Y	Y	Y	N	N	Y	Y	Y	N	Y	N	X	Y	N	N	N
Total		16	9	6	13	1	3	11	2	1	10	3	12	8	0	6	0
%		94	53	35	77	6	18	65	12	1	59	18	71	47	0	35	0
(1) Country Code according to ISO 3166-1																	

Appendix A – Answers to the Questionnaire on Mid Span Clearances

A.2 - Answers to Questions 8 to 15

Question		**8.**	**9.**	**10. Galloping**			**11. Ice dropp.**			**12.**	**13.**	**14. Live line**			**15.**
Country		**Table of load cases**	**Same cases for strength**	**Galloping taken into account**	**Different for all spans**	**Required range of clearances**	**Ice dropping effects**	**Same for all spans**	**Required range of clearances**	**Fault currents taken into account**	**Same clearances if different circuits**	**Live line taken into account**	**Which min clearances**	**Which procedures & conditions**	**Other cases**
(1)		**8**	**9**	**10a**	**10b**	**10c**	**11a**	**11b**	**11c**	**12**	**13**	**14a**	**14b**	**14c**	**15**
1	AU	-	N	N	-	-	N	-	-	N	Y	Y	X	-	X
2	BE	X	N	Y	Y	X	Y	Y	X	N	Y	N	-	N	-
3	BR	X	N	N	N	-	N	-	-	N	Y	Y	X	N	X
4	CZ	X	N	N	-	-	Y	Y	X	N	Y	N	X	N	-
5	DE	X	N	P	-	-	N	-	-	N	Y	N	-	N	-
6	FI	-	N	N	-	-	N	N	-	N	N	N	-	N	-
7	FR	X	N	N	-	-	Y	Y	-	Y	N	Y	-	N	-
8	GB	-	N	N	-	-	N	-	-	N	-	-	-	-	-
9	IT	-	N	P	Y	-	N	N	-	N	Y	-	-	N	-
10	JP	X	N	Y	Y	X	Y	N	X	N	Y	Y	X	Y	X
11	LT	X	N	Y	N	-	N	N	-	N	Y	N	-	N	-
12	NL	X	N	Y	Y	X	N	N	-	N	Y	N	-	N	-
14	NO	X	N	N	N	-	Y	N	X	N	Y	N	-	Y	-
13	NZ	X	N	N	N	-	N	N	-	N	Y	N	-	N	-
15	RS	X	N	N	N	-	N	N	-	N	Y	N	-	N	-
16	UA	X	N	Y	Y	-	Y	N	-	N	Y	N	-	Y	-
17	ZA	-	N	N	N	-	N	-	-	N	Y	Y	X	N	X
Total		12	0	5	5	3	6	3	4	1	14	5	5	3	4
%		71	0	29	29	18	35	18	24	6	82	29	29	18	24
(1) Country Code according to ISO 3166-1															

Appendix B - Questionnaire

Cigre SC22 Working Group 06

Task Force Mid-span Clearance

Your Name:	Position: ......
Company:	
Adress:	
Phone No.:	Fax No.: ......
E-mail:	

The task force on Mid-span Clearance is a continuation of the work by the task force on Tower Top Geometry that was published as Technical Brochure No.48 (June 1995). The aim of this questionnaire is to establish the methods used for determining minimum clearances between individual phase conductors and between phase conductors and earth wires in mid-span.

Terms and definitions

Withstand voltage – the value of the test voltage to be applied under specified conditions in a withstand test, during which a specified number of disruptive discharges is tolerated. The withstand voltage is designated as:

a) conventional withstand voltage, when the number of disruptive discharges tolerated is zero. It is deemed to correspond to a withstand probability P_w = 100% (this is particularly relevant to low voltage technology)

b) statistical withstand voltage , when the number of disruptive discharges tolerated is related to a specified withstand probability, e.g. P_w = 90%

Highest system voltage – the highest value of operating voltage which occurs under normal operating conditions at any time and any point in the system

Lightning impulses (fast front overvoltages) – a voltage impulse of a specified shape applied during dielectric tests with a virtual front duration of the order of 1 microsecond and a time to half value of the order of 50 microsecond

Switching impulses (slow front overvoltages) – a voltage impulse of a specified shape applied during dielectric tests, with a time to crest of 100 to 300 microseconds, and a time to half value of a few milliseconds

Temporary overvoltages – oscillatory overvoltages of the power frequency at a given location, normally of relatively long duration, and which are undamped or weakly damped

Power frequency voltages – the r.m.s. value of sinusoidal power frequency voltage that the equipment can withstand during tests made under specified conditions and for a specified time

1. Standards and/or methods

a) Is there a national standard, regulation, rule or a law used in your country (or area or region or utility) which specifies minimum mid-span clearances? If so, please identify.
yes/no

b) Are there any other design methods used in your country (or area or region or utility) for determining mid-span clearances and/or are there other specified approaches in your current design practices, e.g. customer‘s project specification? If so, please give a short description.
yes/no

2. Determining of mid-span clearances

Are the required mid-span clearances in your current design practices determined by one of the following methods?

a) values (clearances) directly specified in a standard or project specification. If so, give a short description.

yes/no

b) values (clearances) calculated according to empirical equations given in standards, i.e. deterministic method. If so, give a short description.

yes/no

c) values (clearances) calculated by a probabilistic method. If so, give a short description.

yes/no

d) values (clearances) determined by any other method. If so, give a short description.

yes/no

3. Mechanical load cases (loads)

Which methods do you use in your current design practices that establish the mechanical load cases (loads) for determination of mid-span clearances

a) deterministic methods? If so, give a short description.

yes/no

b) simplified probabilistic methods? If so, give a short description.
yes/no

c) probabilistic methods? If so, give a short description.

yes/no

4. Withstand voltages

What methods do you use in your current design practices for determining withstand voltages?

a) required withstand voltages are directly specified in a standard or in a project specification. If so, give a short description.
yes/no

b) required withstand voltages are determined by probabilistic methods, i.e. withstand voltages are determined by statistical distribution of overvoltages on the line and a required probability of flashover performance level. If so, give a short description.
yes/no

5. Levels of overvoltages

If the following overvoltages are used in your current design practices for determining mid-span clearances, please complete the table for all highest system voltages in your country (or area or region or utility) within each grouping. State the value of the overvoltage, if possible, and indicate whether the value is specified in a national standard (NS) or other source (AS).

Range of highest system voltage [kV]	123-145	145-170	170-245	245-300	300-420	420-525	525-
Highest system voltage [kV]	......	......	......	......	......	......	......
Lightning impulses (fast front overvoltages) [kV]	....	....	....	....	....	....	....
Switching impulses (slow front overvoltages) [kV]	....	....	....	....	....	....	....
Temporary power frequency overvoltages [kV]	....	....	....	....	....	....	....
Power frequency voltages [kV]	....	....	....	....	....	....	....

Your notes to the table:

6. Mechanical reliability of transmission lines

Please take into account your response to question No.3.

a) Do you employ different reliability levels in your current design practices to ensure appropriate mechanical performance? If so, give a short description.

yes/no

b) If affirmative, do these reliability levels influence load cases (loads) used for determining mid-span clearances? If so, give a short description.
yes/no

7. Electrical reliability of transmission lines

Please take into account your response to question No.4.

a) Do you employ different reliability levels in your current design practices to ensure appropriate electrical performance (probability of a flashover)? If so, give a short description.

yes/no

b) Are these reliability levels relevant to the determination of mid-span clearances? If so, give a short description.

yes/no

8. Load cases used

Table “Load cases” states a range of load cases normally adopted for calculation of mid-span clearances. Please complete the table in accordance with your current design practices.

9. Comparison of load cases

Load cases (loads) for determination of mid-span clearances vs. load cases (loads) for calculation of component strengths (conductors, fittings, towers etc.)

Are the load cases (loads) the same for determining both mid-span clearances and components strengths. If yes, provide a short description.
yes/no

10. Low frequency mechanical oscilations of conductors

a) Does your current design practice require the minimum mid-span clearance to be determined by a dynamic load case, characterised by a wind induced low frequency and high amplitude mechanical oscillation (galloping) of conductors? If so, give a short description.

yes/no

b) Is the required minimum mid-span clearance the same for all span lengths within a line/tension section?

yes/no

c) What is the required range of minimum mid-span clearances and withstand voltages appropriate to the former? Give a short description.

..

11. Ice dropping

a) Does your current design practice require the minimum mid-span clearance to be determined by a dynamic load case, characterised by a low frequency and high amplitude mechanical oscillation of conductors with consideration of ice dropping affects? If so, give a short description.

yes/no

b) Is the required minimum mid-span clearance the same for all span lengths within a line/tension section?

yes/no

c) What is the required range of minimum mid-span clearances and withstand voltages appropriate to the former? Give a short description.

..

12. Dynamic forces caused by short-circuit currents

Does your current design practice require the minimum mid-span clearance to be determined by the dynamic motion of conductors associated with fault currents? If so, give a short description.

yes/no

13. Transmission lines with 2 or more systems (circuits)

Are the minimum mid-span clearances between phase conductors in one system identical to the mid-span clearances between phase conductors of a different system where transmission lines carry 2 or more systems? If so, give a short description.

yes/no

14. Live line maintenance

a) Does your current design practice take live line maintenance procedures into account when determining minimum mid-span clearances? If so, give a short description.

yes/no

b) If affirmative, what are the required minimum mid-span clearances or withstand voltages?

..

c) Which live line procedures/conditions are accounted for?

..

15. Other cases

Does your current design practice consider other cases not stated above for determining minimum mid-span clearances? If so, give a short description.

yes/no

Forward your response to the author.

Pavel Fronek
EGE – Inzenyring s.r.o.
Starochodovska 68/41
149 00 Praha 4
Czech republic
Phone No.: +420 2 67199 159
Fax No.: +420 2 67199 152
E-Mail: fronek@egei.cz

Thank you for your time and effort.
July 12, 2002

Table – Load cases

Load case	**tempe rature [°C]**	**wind speed [m/s]**	**wind pressure [N/m^2]**	**weight of ice [N/m]**	**highest system voltage [kV]**	**required withstand voltage [kV]**	**required phase to phase clearance [m]**	**required phase to earth wire clearance [m]**
1. maximum temperature of conductor t_{max}, no wind, no ice	......	....	....	....	....	....	....	....
					....	....	....	....
					....	....	....	....
					....	....	....	....
2. minimum temperature of conductor t_{min}, no wind, no ice	......	....	....	....	....	....	....	....
					....	....	....	....
					....	....	....	....
					....	....	....	....
3. other temperature t_{def1}, no wind, no ice (e.g. the average year temperature)	......	....	....	....	....	....	....	....
					....	....	....	....
					....	....	....	....
					....	....	....	....
4. temperature t_{def2}, low wind v_{low}, no ice	......	....	....	....	....	....	....	....
					....	....	....	....
					....	....	....	....
					....	....	....	....
5. temperature t_{def3}, moderate wind v_{mod}, no ice	......	....	....	....	....	....	....	....
					....	....	....	....
					....	....	....	....
					....	....	....	....

Load case	**tempe rature [°C]**	**wind speed [m/s]**	**wind pressure [N/m^2]**	**weight of ice [N/m]**	**highest system voltage [kV]**	**required withstand voltage [kV]**	**required phase to phase clearance [m]**	**required phase to earth wire clearance [m]**
6. temperature t_{def4}, high wind v_{max}, no ice	......	....	....	....	....	....	....	....
					....	....	....	....
					....	....	....	....
					....	....	....	....
7. temperature t_{def5} (usually 0°C to –10°C), no wind, maximum ice q_{max}	......	....	....	....	....	....	....	....
					....	....	....	....
					....	....	....	....
					....	....	....	....
8. temperature t_{def6} (usually 0°C to –10°C), high wind v_{def1}, reduced ice q_{def1}	......	....	....	....	....	....	....	....
					....	....	....	....
					....	....	....	....
					....	....	....	....
9. temperature t_{def7} (usually 0°C to –10°C), reduced wind v_{def2}, maximum ice q_{def2}	......	....	....	....	....	....	....	....
					....	....	....	....
					....	....	....	....
					....	....	....	....
10. temperature t_{def8} (usually 0°C to –10°C), no wind, different uniform ice on upper and lower conductor q_{def3} resp. q_{def4}	......	....	....	....	....	....	....	....
					....	....	....	....
					....	....	....	....
					....	....	....	....

Load case	tempe rature [°C]	wind speed [m/s]	wind pressure [N/m^2]	weight of ice [N/m]	highest system voltage [kV]	required withstand voltage [kV]	required phase to phase clearance [m]	required phase to earth wire clearance [m]
11. temperature t_{def8} (usually 0°C to –10°C), no wind, non-uniform ice on adjacent spans q_{def3} resp. q_{def4}	......	....	....	....	....	....	....	....
					....	....	....	....
					....	....	....	....
					....	....	....	....
12. temperature t_{def9}, no ice, different wind on windward and leeward conductor v_{def3} resp. v_{def4}	......	....	....	....	....	....	....	....
					....	....	....	....
					....	....	....	....
					....	....	....	....
13. temperature t_{def9}, specified ice q_{def5}, different wind on windward and leeward conductor v_{def5} resp. v_{def6}	......	....	....	....	....	....	....	....
					....	....	....	....
					....	....	....	....
					....	....	....	....
E. Empirical equation – required clearances dependant on sag, span, tension, voltage at specified conditions ..	......	....	....	....	....	....	....	....
					....	....	....	....
	......	....	....	....	....	....	....	....
					....	....	....	....
Other cases not stated	......	....	....	....	....	....	....	....
					....	....	....	....
					....	....	....	....
					....	....	....	....